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PARTNERSHIP BETWEEN GEOLOGY AND GEOPHYSICS IN PROSPECTING FOR OIL*

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It is my privilege to extend to the American Association of Petroleum Geologists, on this celebration of its silver anniversary, the felicitations of the Society of Exploration Geophysicists. The contemplation of twenty-five years of sound and progressive history is no doubt a source of deep satisfaction to those who founded the Association and to many others who helped to make it grow. Simultaneously, the Society which I am here representing is celebrating its tin anniversary. When this coincidence first came to my attention, I hoped to find that the alloying of silver and tin, a noble and a base metal, produces a product with useful properties not possessed by either component alone. The rhetorical advantages which would have followed are obvious. The metallurgical literature, however, dashed this hope so that this allegorical approach to my subject had to be abandoned.

That there exist broad areas of common interest between geologists and geophysicists is almost too obvious to require mention. That this is realized is evidenced by the substantial overlap in the membership of our respective professional organizations. In fact, three out of every eight members of the Society of Exploration Geophysicists are members of the American Association of Petroleum Geologists. Dr. Donald Barton, who probably contributed more than any other one man to the founding of our Society, was its first president and later also president of the Association.

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The existence of areas of common interest and their recognition are two important factors which invite partnership. It is quite generally realized that the two professional groups which we represent deal with substantially the same objectives, and that it is only in the manner in which they are approached that we differ. Each has a contribution to make to the achievement of the common goal. This is the essential prerequisite to a partnership. It is in that light that I like to view the cooperative effort of our two professional groups in the business of prospecting.

Partnerships vary widely in character. They most completely fulfill their purpose when each partner appreciates fully the special talents of the other and when a mutual understanding exists as to how they can best be coordinated so as to produce the most favorable results. That this mutual understanding is insufficiently developed between geologists and geophysicists is well known. That its cultivation is worthy of the best efforts of all concerned is a point I wish to make. The more effective coordination of the geological and geophysical aspects of prospecting seem to me the outstanding need of the day in this branch of the oil industry. Its accomplishment will in my judgment pay greater dividends than any advance which can be anticipated in the techniques of either geology or geophysics.

The result of geophysical prospecting depends quite as much on the quality of the reaction to the geophysical picture as on the merit of the data on which the reaction is based. With full realization of the shortcomings of many geophysical pictures, I venture to suggest that in the past the data have in general been better than the utilization of them. In the nature of things, this must be a matter of opinion, but it is an opinion that is widely held among competent geophysicists.

The process of defining practically any subsurface structure on the basis of geophysical or any other evidence is almost invariably similar to a detective job in which the available evidence is fragmentary. The fragments have to be fitted together in the most reasonable manner. The resulting contour map cannot possibly portray adequately what is strong and what is weak. Yet this map is too often the sole basis of all subsequent action. Geologists have been known to become annoyed when the geophysicist qualifies his picture with ifs and buts. Yet a knowledge of the weaknesses in the evidence is necessary to correctly appraise the risks which are being faced. Although it has been said facetiously that if management fully understood the risks, few would be undertaken, I nevertheless believe that the correct appraisal of the risks being assumed is essential to a sound prospecting program. When

the evidence available is wholly geophysical the chief geologist and perhaps even management cannot afford to consider less than all the geophysicist knows about the prospect.

In the early days of geophysical operations it was a quite common practice to withhold from geophysicists information already available concerning the areas in which they were working. The purpose, no doubt, was to prevent the geophysical findings from being biased by the pre-existing knowledge. The circumstances surrounding much of the early work probably made this precaution necessary, but the effect unquestionably was to retard the development of the geophysical art. Fortunately this attitude has been disappearing rapidly and today only erosional remnants remain, usually capped by exceptionally resistant rock.

It may be useful to enumerate some of the factors on which the success of geophysical prospecting depends. This is done in the following table.

FACTORS ON WHICH THE SUCCESS OF GEOPHYSICAL PROSPECTING DEPENDS

1. Choice of a geophysical program.
   a. To be in harmony with the general prospecting policy of the company.
   b. To defend most effectively against competitive activity.
2. Choice of a geophysical method.
   a. In view of the general geology of the area to be prospected.
   b. In view of the nature and extent of prospecting already done in the area.
   c. In view of the physiographic and geographic character of the area to be prospected.
   d. In view of competitive activity.
   e. In view of the relative availability of different methods.
   f. In view of relative costs.
3. The control of geophysical operations by
   a. Considerations of economy.
   b. Legal considerations.
   c. Technical considerations.
4. The quality of the geophysical results.
5. The quality of the follow-up of geophysical findings.

This list is undoubtedly incomplete and the classification it presents capable of improvement, but it will serve our purposes as it stands. It indicates that the factors which contribute to success or failure are numerous and often strongly interdependent. That is why management finds it so difficult to analyze such failures as occur and to locate the weak spots and remedy the trouble. It explains why the medicine may be handed out to the wrong department and justifies the suspicion that at times the prescriber should take the medicine himself. Everybody who deals administratively with exploration should have such a list but I doubt if very many people have one.

A geophysical program may be a model of excellence in all other respects and fail simply because it does not fit in with the general prospecting policy of the company. This lack of adaptation may apply only to parts or certain aspects of the operation as well as to the whole. The maladjustment of program to needs is a fundamental weakness, the avoidance of which is a primary prerequisite to success.

An adequate defense against competitive activity has varied aspects and consequently in considering this angle of the geophysical program there must be taken into account general policy, the nature of the geologic province and available techniques as well as the nature and volume of the competing effort.

In deciding which geophysical method or combination of methods to use under a given set of circumstances, close attention must be given to the inherent suitability of each method for investiagting the problem under consideration. It may not be feasible to use the most suitable one and, as a matter of expediency, a second or third choice procedure may have to be adopted. There is a real danger that concessions to expediency become habitual and that they are made when the need for making them does not exist. Constant effort is required to assure the use of the best possible method which conflicting practical considerations will permit and to prevent the complete devitalization of the geophysical attack by obstacles which loom greater in the minds of men than they do in actual fact.

Time does not permit our discussing in detail the various factors which have been mentioned as having a bearing on the success of geophysical operations. It is to be noted that they can fail at many points and that in the initiation, execution and exploitation of geophysical programs, executives, geologists and geophysicists have intricately interlaced opportunities and responsibilities. The well coordinated cooperation of all is necessary to success.

By way of illustration, brief mention may be made of a successful geophysical campaign of which I have intimate personal knowledge. Very late in 1936 or very early in 1937 a well drilling in Lamar County, Mississippi was reported to have encountered anhydrite at relatively shallow depth. To geologists familiar with the stratigraphy of the area, this immediately suggested cap-rock. It seemed probable that on drilling deeper the well would encounter salt and that the discovery of the first salt dome to be found in Mississippi would thus be confirmed. As you all know, this anticipation was realized a short time later. My company rushed a gravimeter party to the environment of the well and the survey made promptly revealed the existence of a gravity minimum typical of a piercement type salt dome. A second gravimeter party was moved into the area and a complete systematic gravity survey of a substantial part of southern Mississippi was initiated. The existence of a salt dome basin of considerable extent was revealed. Over a period of many months salt dome prospects were discovered at an average rate of one per week. Since the gravity survey systematically covered the entire area, nothing could be learned from the operation as to what if anything was being found and it was not until the leasing was being done that any information became available.

The geophysical cost of this operation per prospect was nominal. The land costs were also quite moderate. This campaign allowed the assembly of lease blocks on favorable prospects in an area of which the oil possibilities remained to be ascertained. The cost per block undoubtedly represented a new low in discovery cost for the average of a number of prospects.

I will leave it to the reader to analyze this example for the elements of its success. It was an example of partnership at its best. The availability and smooth performance of gravimeters was of course an essential prerequisite. Work on the development of these instruments had been begun four years earlier. Had this not been true the campaign in Mississippi would have had an entirely different history, a much less favorable one.

This brings to mind the question as to how actual prospecting by geophysical methods should be related to pertinent research and development. The needs and problems in any field of endeavor are the more easily perceived the closer one is to the job. It is best to have instruments for field use designed only by men who have experienced the circumstances of actual field operation. In the nature of things

some separation of the research and development from the operating function is unavoidable. But the unfavorable effect of this separation can be minimized by a judicious and continual transfer of men between the two groups. No amount of description will fully substitute for actually seeing a thing. No system of reporting, however complete, will adequately inform a research and development group regarding the problems of the operating group. It is as true in geophysics as in other fields that necessity is the mother of invention. The necessities in geophysics are faced primarily in the field operations. In line with these considerations a geophysical staff is conveniently divided into three classifications:

a. Primarily research and development men.
b. Men fitted for both development and field operations.
c. Primarily field operators.

The men in the middle group are those who should be shifted back and forth between the other groups.

The normal conduct of geophysical operations involves a complex series of compromises between considerations of geology, geography, geophysics, finance, law and related management policies. In order that the subject may be viewed objectively and in perspective, it is necessary that the representative of each specialty have some working knowledge of the other matters which are involved, and that some machinery exists for developing a composite picture to which each factor contributes no more and no less than its appropriate part. This is a fallow field for the partnership of geology and geophysics.

THE HISTORY AND DEVELOPMENT OF SEISMIC PROSPECTING*

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ABSTRACT

An historical outline of the development of modern seismic prospecting methods is presented. Particular attention is given to a review of the very early work which laid the foundations upon which a rapid growth of the art took place when the facilities for adequate instrumentation became available.

A number of writers, particularly Barton[1] and DeGolyer[2] have presented sketches of early work in the seismic field. Nevertheless, it seemed desirable to give a more detailed account of these early developments and of the state of the art just prior to the time that the seismic method became a powerful tool for petroleum exploration. It is not generally appreciated that the stage had been carefully set and the players were ready to perform in their new roles as prospectors. Practically all that was needed to start the play was the insatiable thirst of a rapidly growing mechanization.

Consequently, the first part of this paper will be on "Developments Leading Up To Prospecting." The remaining subject matter can be rather readily classified into "Prospecting by the Refraction Method" and "Prospecting by the Reflection Method."

The earliest work in the field of artificial seismology was carried on by Robert Mallet, who had a surprisingly clear understanding of what could be accomplished by the use of artificial seismic waves. In 1846 he read a paper[3] in which problems concerning the constitution of the earth were discussed and in which he pointed out that different kinds of rocks might have diagnostic velocities. He also proposed the use of this method of exploration for obtaining information on those vast areas of the globe which are covered with water and about which so little is known. In 1851 he reported on the results of some field experiments[4] in which the velocities of artificial seismic waves were measured in granite and loose sand. These were undoubtedly the first experiments of this kind and for that reason are of par-

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[1] For references see Bibliography at end of paper.

ticular interest. A buried charge of gunpowder was detonated and the waves so generated were picked up at a distance on a seismoscope. The seismoscope consisted of a bowl of mercury from the surface of which was reflected a spot of light in the from of cross hairs. This spot was observed through a small telescope. When the surface of the mercury was agitated the image disappeared. Consequently, the arrival of the wave was signified to the observer by the appearance of surface ripples which destroyed the image. The starting of a chronograph by the observer fired the shot electrically, and as soon as the wave appeared at the seismoscope the same observer stopped the chronograph. Thus the time of transit of the wave was determined and since the distance between the shot and the seismoscope had been carefully measured, the velocity could be calculated. Even though his experiments combined all the necessary elements, Mallet was unable to measure the true longitudinal velocity of the materials through which the wave was passing because of the low sensitivity of his seismoscope. He did, however, obtain different velocities for different materials. These ranged from 825 feet per second for sand to 1665 feet per second for granite.

In 1876 General H. L. Abbot[5] of the Corps of Engineers of the United States Army took advantage of an explosion of 50,000 pounds of dynamite at Hallets Point to measure the velocity of transmission of seismic waves. He set up several seismoscopes of the Mallet type in different azimuths, and at distances varying from five to twelve miles from the explosion. The velocities obtained were substantially higher than those of Mallet, ranging as high as 8000 feet per second. When these results were made public they provoked Mallet into publishing some rather caustic criticism of, not only the results, but also the method. Abbot's reply was a report on a second series of experiments which not only confirmed his earlier results but also dealt with some new aspects of the problem. Abbot had realized that the earliest arrivals of energy might not create enough disturbance of the mercury surface to be detected. Consequently he increased the power of the telescope used for viewing the mercury surface and found that the calculated velocities were increased by more than 2000 feet per second. Another purpose of this later group of experiments was to determine whether increasing the charge would increase the velocity. Higher velocities *were* obtained with the larger charges. Furthermore, as the distance between shot and seismoscope was increased, the velocity appeared to decrease. Abbot failed to appreciate that these two effects

were due to the lack of sensitivity of his seismoscope rather than to any physical laws.

A few years later Milne and Gray[6] conducted more elaborate experiments in Japan in which they used the impact of a falling weight to generate the waves. These were recorded by mechanical seismographs on moving smoked glass plates. The shock instant was recorded on the same plates. Later, explosives were used in order to get greater amplitudes.

In order to find out the nature of the vibrations they recorded the different components of motion of the waves. They sought to discover the effect of irregular terrain by placing the seismographs on steep hills, and by having a pond between the shot and the semisograph. They studied variations in amplitude with distance from the shot.

The distances over which they recorded were short, but they recorded simultaneously with two seismographs in line with the shot and at different distances. These were probably the first profiles ever shot.

Milne showed that different materials had different velocities but his values were lower than those of Abbot (5000 feet per second in schist, 3500 feet per second in tuff).

Fouqué and Lévy in 1889[7] added to the experimental work by making some careful velocity measurements in mines. The improvement in apparatus attributable to them is a photographically recording seismoscope of considerably higher sensitivity than had been previously used. The velocities obtained checked in general the higher values of Abbot. They, too, showed the marked variation in velocity of different formations (granite 10,000 feet per second, Permian sandstone 4000 feet per second).

Hecker,[8] in 1900, worked on experiments using large charges of gunpowder (1500 kg) and recorded with mechanical seismographs both the longitudinal and transverse components along a line at nine points some 200 feet apart. This was, indeed, a profile as we know it today. Unfortunately he was unable to show the velocity variations with depth which had been his hope. However, he did recognize that the high amplitude, low velocity pulse usually observed on the record was preceded by a high velocity, low amplitude tremor which it was not possible to measure because of low sensitivity.

Turning now to the theoretical development of the method, Schmidt in 1888 published a comprehensive paper[9] in which he pointed out that the wave velocity would increase with depth below

the surface (a moot point at that time). He further discussed the construction of travel time curves for natural earthquakes.

In 1899 Knott wrote concerning the propagation of seismic waves and their refraction and reflection at elastic discontinuities.[10]

Many of the experiments mentioned above had hinted at practical uses of the method but it remained for Belar, in 1901, to state such an objective in clear and concise language. He said:

> . . . the modern, sensitive instruments may easily be used to special advantage wherever we wish to learn beforehand the composition of the earth crust to carry out to advantage, e.g., the construction of a tunnel. A series of tests carried out along the tunnel line on the surface would be sufficient to enable us to form a reliable judgment on the elasticity conditions, or, say, on the rigidity of the ground, of an earth stratum which would not be accessible by other means.

By 1907 Wiechert and Zoeppritz had worked out the theory of seismic wave transmission through the earth, and in a monumental work[11] gave solutions to the problems of seismic wave propagation, refraction and reflection, which placed the theoretical solution of the problem far ahead of the experimental. Thus the situation became somewhat analogous to Maxwell's mathematical treatment of electromagnetic waves which was so far ahead of the experimental work that it was many years before Hertz observed many of the properties of these waves which had been predicted by Maxwell.

Zoeppritz and Geiger, working together, extended somewhat the work of Wiechert, and in 1910 Wiechert published another paper[12] containing a paragraph which so exactly fitted into the subsequent practice of refraction profiling that it is considered worthwhile to repeat it here.

> The farther from the origin the earthquake waves are observed at the earth's surface, the deeper the rays have penetrated into the earth and the more of the assumed layers they have therefore traversed. If one therefore proceeds from the origin gradually in the distance, then initially only the first, later also the second, and then the third, and so on of the layers will come into action. One proceeds correspondingly with the computation. From the observations in the vicinity of the origin one draws conclusions first regarding the constants . . . of the first layer . . . . The paths of all rays through this layer can then be calculated. From the paths of those rays which penetrate the first layer but remain close to it one draws conclusions regarding . . . the second layer, and so on, in this manner.

Other names such as Sieberg, Benndorf, Wilip, and Von dem Borne should be added to the list of early workers. Their contributions have

not been included because it was possible to present a fairly accurate picture of early developments without going into further detail.

Thus the early investigators had developed the idea of artificial seismic waves generated by high explosives. They had developed instruments to pick up the tremors, and to record and time them. They had developed an entirely adqeuate theory of wave propagation, which included profiling as a means of obtaining layer velocities and thicknesses. Lastly, they had suggested practical uses of the method. This lead us quite naturally to the second part of the paper.

PRACTICAL DEVELOPMENT OF REFRACTION METHODS

Shortly after the publishing of Wiechert's paper, thought on this subject took a more practical turn as scientists began to realize that here might be a powerful commercial tool. Mintrop, who had been a student of Wiechert's made some vague references in this direction in an article published in 1910, while Prince Galitzin in 1913 made the following statement:[13]

The knowledge of the exact form of the hodograph (or travelling time curve) is of very especial importance for practical seismometry and the highest possible improvement of the same should be striven for. To be considered here are the characteristics of the geologic structure of the upper formations of the earth.

In 1914 Wilip showed appreciation of the practical aspects of the problem when he wrote:[14]

Up to the present it has not been possible to quite accurately determine the hodograph (travelling time curve) of the seismic rays for shorter distances, and the topmost layers of the earth's crust. However, it is the very characteristics of the vibrations of the topmost layers of the earth's crust which could be of great practical importance in that they may give us information about those parts of the earth's crust in which mining operations are carried on.

At about this time the Great War broke out and extensive work was done by the various Army Staffs in attempting to use the air waves generated by the explosion, and the refracted waves caused by the recoil of the big guns for the purpose of triangulating in the enemy gun positions. It was soon discovered that geological irregularities caused such differences in the traveling times of the refracted waves that this method was not particularly successful. Considerably more progress was made, however, in the use of the air wave.

Mintrop, already interested, had his attention further focused on

the possibilities of the refraction method by his war work and in 1919 applied for a patent in Germany covering the use of refraction profiling for locating the depth and type of subsurface formations.

In 1923 the Seismos Gesellschaft, organized in Germany by Mintrop, started refraction work in Mexico for the Mexican Eagle Oil Company. In the latter part of the same year the Marland Oil Company tried a Seismos crew along the fault line play near Mexia and also on the coastal plain of Texas. They also did some work in Oklahoma. The results of this work were of indifferent quality but at least they did demonstrate that the method had some possibilities. Work was started by the Seismos for the Gulf in 1924 in the Gulf Coast and in a short time the Orchard dome had been discovered. This first discovery was followed by several more in 1925.

L. P. Garrett of the Gulf was responsible for this company's early trial of the method and to him goes the credit for starting the use of refraction fans. The Germans had experienced great difficulty with the interpretation of their profiles. Because of the type of section in the Gulf Coast it was almost impossible to obtain easily recognizable breaks in the velocity of the different layers and to calculate the depths of these layers. Garrett suggested that two equal length shots, one across a known dome and the other off the dome, should show marked time differences. The field trial was highly successful because of the relatively high velocity of the salt and it was at once apparent that a geometrical arrangement such as a fan would give this time comparison over a large area from a minimum number of shot points. This was a tremendous step forward for had it been necessary to use profiling, as originally intended, the cost of coverage would have been very much greater.

Meanwhile E. L. DeGolyer, who had been responsible for trying the method in Mexico, was following the results in Oklahoma and Texas with great interest and with a full appreciation of its potentialities. With the purpose of further developing the new method he organized the Geophysical Research Corporation in 1925 with J. C. Karcher in charge. Karcher was quite familiar with the problems involved because of previous work in this field. This will be described later in the paper. The new company immediately set out to design entirely new equipment. In less than a year the apparatus was ready for field use and in 1926 the first crew went to work for the Gulf. Many changes in both apparatus and field technique were effected from the very beginning. The newly designed electrical detectors and amplifiers

were many times more sensitive than the German mechanical seismographs. Radio communication between shot point and detector point permitted the sending of the instant of explosion by radio, whereas the Germans estimated this instant by using the air wave and the surveyed distance. Distances between shot and detector were found by the use of the air waves, whereas the Germans used surveyed distances. The above advantages greatly increased the speed of shooting and consequently the cost of coverage was reduced substantially. Vast areas were explored with the discovery of many domes as a result. Perhaps the most remarkable feat of the whole Gulf Coast program was the shooting of millions of acres of marshy and swampy coastal Louisiana for the Louisiana Land and Exploration Company. The area, unworkable by the torsion balance because of terrain conditions, with extremely poor maps for guidance, was subjected to a network of fans with boats as a means of transportation. A few short months of intense effort resulted in the discovery of a dozen domes. Several of them, such as Caillou Island, Leesville and Lake Barre, have been quite prolific oil producers.

This program of covering the Gulf Coast of Texas and Louisiana lasted about four years during which time more than forty domes were discovered. During the latter part of the period, oil was discovered in East Texas off the edge of the Boggy Creek dome. There was an immediate influx of crews into the East Texas geosyncline. A number of shallow domes were found but none of them have been profitable. However, the program led to the discovery of Van which at that time was difficult to diagnose because of the absence of salt velocities.

The companies who were most active in this refraction program were the Gulf, Humble, Roxana (Shell), Pure and Louisiana Land and Exploration Company. The greater part of this work was done by the Seismos and the Geophysical Research Corporation. Other consulting companies were the Petty Geophysical Engineering Company, Burton, McCollum, and Frank Rieber. The Humble and Shell did most of their own exploration work.

During this program occasional refraction profiles were run in order to have some idea of the form of the time distance curve, and in order to find out at what distance from the shot point marked changes in the slope of the curve occurred. Two major changes due to the so-called first and second semi-consolidated layers were recognized although it was difficult to tie them down geologically. There seemed to be some basis for considering that the first of these changes corre-

sponded to the Miocene-Oligocene contact. On shallow domes, where salt velocities could be obtained, profiles were frequently used for the purpose of detailing these domes.

With such an extended program in the Gulf Coast it was quite natural for the method to be given a trial in California where the geological section is similar. The work there was disappointing primarily because there were no high speed intrusives, such as salt domes, which could be found by the fanning process. Consequently it was necessary to run profiles and since, in general, there were no high velocity layers, the data was indefinite. There was some moderately successful work on the east side of the San Joaquin Valley in tracing the westward plunge of the very high velocity granite.

In the West Texas Permian basin, the section consisting of rather definite layers of low speed Triassic and Permian red beds, higher velocity salt and anhydrite and still higher velocity limestone, was definitely favorable for refraction profiling. In these profiles each one of the above layers could be recognized by its velocity and the depth to the top of each layer calculated. It was never possible to get a high degree of accuracy into such work, but it did serve to indicate the more pronounced structures, and certainly the program may be termed partially successful. The greatest drawbacks were the high cost of the work (dynamite charges were excessive) and the inherent inaccuracies in the method. There is a good reason why the Seismos did very little if any work of this kind. The mechanical seismograph was too insensitive to pick up the very low amplitude waves which had penetrated the lime.

It is necessary to return to the Gulf Coast for a moment. The diagnostic properties for salt domes were: high absorption, 15,000 feet per second velocity and time leads of from .3 to .5 sec. Occasionally anomalous results were being obtained in local areas where none of these conditions were satisfied. These abnormal areas had leads of the order of .1 to .2 sec. and no amount of profiling revealed a salt velocity. As was right and proper, these anomalies were set aside to await the advent of an exploration method of higher resolving power, and when the reflection seismograph made its appearance there were a number of such areas for it to detail. Bosco and Conroe are examples which have accounted for large quantities of oil.

THE REFLECTION METHOD

One of the first practical applications of artificial seismic waves was to sonic depth-finding, and the use of reflected waves in this con-

nection turned out to be highly successful. Reginald Fessenden, who was mainly responsible for this early development, appreciated the possibility of extending this success into the exploration field and in 1914 applied for a patent. The patent covered the use of both reflected and refracted sound waves for locating mineral bodies. The earth was energized by a mechanical oscillator similar to the one being used in marine work and the wave after reflection or refraction was picked up by a microphone. From the time of transit of the wave it was possible to tell whether it had suffered any unusual deviation.

In 1917 J. C. Karcher was engaged at the Bureau of Standards in developing a suitable detector for the air waves generated by gun explosions. Associated with him were Dr. W. P. Haseman, under whom Karcher had studied at Oklahoma University, E. A. Eckhardt and Burton McCollum. These men had all talked and corresponded on the possibility of using reflections for locating oil-bearing structures. Karcher also had extensive correspondence with Dr. J. A. Udden, of the University of Texas, relative to the geology of Texas and the possibility of getting reflections there. In 1919 Karcher applied for a patent covering reflection prospecting. The claims were comprehensive and definite but the Fessenden patent was cited by the patent office as prior art and Karcher abandoned his application.

The Geological Engineering Company was organized in 1921 by Drs. Haseman and D. W. O'Hern, Irving Perrine, Frank Buttram and W. R. Ramsey. Drs. Karcher, Eckhardt and McCollum were invited to join the staff. In the summer and fall of this year, experimental work was carried on in a number of different localities in Oklahoma. Refraction work on the outcrops in the Arbuckle mountains established the fact that the Sylvan shale immediately overlying the Viola limestone was of low velocity whereas the Viola was of extremely high velocity. Consequently, it was expected that this contact should constitute an excellent reflecting horizon. This turned out to be the case and reflections were obtained from the Viola at a depth of several hundred feet. In other areas, well defined reflections were also obtained from various limestones in the Pennsylvanian. Messrs. Geyer and Aurin of the Marland Oil Company lent their assistance in choosing areas in which to work and on at least one occasion a small area was shot out at the expense of that company. There was considerable experimenting with shot hole depth, earth and water tamping, and also with different distances between shot and detector. Although definite progress was made, the founders of the company

became occupied with other matters and the work was discontinued in 1922 with the company finally becoming the property of Mr. McCollum.

In 1920 John William Evans and Bevan Whitney applied for a patent covering the reflection method and in 1922 Burton McCollum applied for the first of a series of patents covering both the refraction and the reflection method of seismic surveying.

When the Geophysical Research Corporation was organized in 1925 it was with the understanding that one of its most important objectives was the development of a reflection technique, and from its very beginning, continuous efforts were made to develop and improve the reflection seismograph. It was found necessary to rather drastically modify the refraction apparatus in order to obtain satisfactory reflection records. For refraction work the whole system was designed to pass the low frequencies. This was necessary in order to pick up the earliest arrivals of energy, the so-called first breaks. Such a system was quite undesirable for reflection work. Frequently a low velocity, low frequency ground wave was recorded together with the reflected wave, and in order to make the reflection stand out on the record it was necessary to use electrical filters which absorbed this low frequency energy. This was not particularly difficult since reflection frequencies were between forty and eighty cycles whereas the ground wave was thirty cycles or less.

In refraction work a party used two or three recording trucks, each with one complete recording unit of detector, amplifier and camera. Early in the development of reflection apparatus the multiple element camera, or oscillograph, was introduced with which four to six complete recording channels could be used. The introduction of this camera not only made the reflections much easier to recognize and calculate, but it aided enormously in correlating, since it permitted the study of rather minute character changes. The customary procedure was to place several detectors in line with the shot, the distance between detectors being of the order of 200 feet with the nearest one about a thousand feet from the shot.

The effect of weathering variations was recognized very early in the work and additional weathering shots were always taken in shallow shot holes near the recording spread. These gave in effect a short refraction profile which was solved as a simple two layer case.

One of the first reflection projects of the Geophysical Research Corporation was on the Nash dome in the fall of 1926. Satisfactory

reflections were obtained from the cap rock. In 1927 and 1928 a shooting program was inaugurated on the Seminole plateau of Oklahoma where the Viola lime was used as a marker. The results, although somewhat uncertain, indicated two high areas, on both of which production was subsequently found. In 1929, in the same area, with improved apparatus and technique, three structures were found. These were tested in 1930 and resulted in the discovery of three oil fields in rapid succession, thereby definitely establishing the value of the method as an exploratory tool.

The Petty Geophysical Company was working on reflection problems during this period, as also were the Humble and Shell, but as far as can be ascertained these companies did no systematic field work prior to 1930 or 1931.

The reflection problem on the Gulf Coast was more difficult. Of much younger age of sedimentation than the Plateau, and with no blanket high velocity limestones or other beds of sharply different velocity in the section, it was difficult to see how use could be made of the haphazard and uncorrelatable reflections which occurred from such a section. Although it was recognized that the "step-out" of the reflection was a function of the dip of the reflecting bed, this fact was not put to use until the Geophysical Research Corporation developed the dip method of shooting in the Gulf Coast in 1929. The method was first used in detailing the Darrow dome.

It was not long until all of the old refraction anomalies were being checked and several of them yielded substantial structures. Torsion balance anomalies were subjected to the same treatment with similar results. After the various leads were checked the whole Coastal area was subjected to a blanket coverage, first with a coarse, then finer and finer, grid.

The success of the reflection method, both correlation and dip, was so immediate and pronounced that it gave rise to a phenomenal growth in seismic activity. By 1937 there were between 225 and 250 crews in this country whereas in 1929 there had been only four.

Very substantial improvements have been made, both in apparatus and technique, during the past ten years. Probably the most important gain has been in the increased stability of the equipment used. Instrumental failure in the field is rare. Practically all of the apparatus in use is sufficiently sensitive to work down to the level of ground unsteadiness. Automatically controlled amplifiers of one kind or another are general. Their sensitivity is either a function of time or of

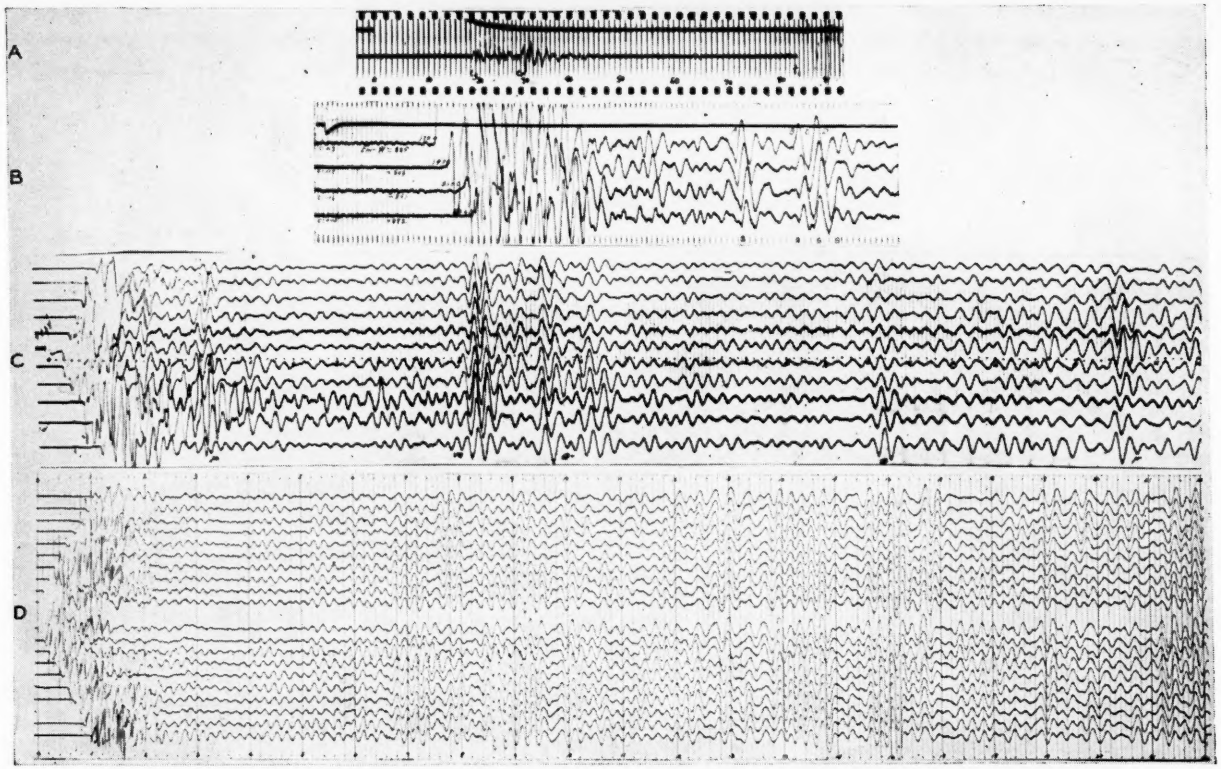

FIG. 1. DIFFERENT STAGES IN DEVELOPMENT OF REFLECTION TECHNIQUE

A. Record showing reflection from Cap of Nash Dome taken in 1926. Similar to those shot in 1921. Charge, one pound; distance between shot and detector, 950 feet. A profile was made by recording several shots at different distances.

B. Shot on Seminole Plateau in 1930. The last large amplitude reflection is correlatable over a large area and is from the Viola Lime. Each shot was recorded at several different distances.

C. Type of record shot in California in 1934. Note the automatic volume control and increasing number of traces.

D. Type of record taken in Victoria County, Texas, in 1940. Note still greater number of traces. The upper half of the record was recorded at right angles to the lower half, giving true dip determination.

Records A, B and C shown through the courtsey of the Geophysical Research Corporation. Record D shown through the courtesy of the United Geophysical Company.

amplitude and they are so adjusted that the early part of the record is compressed and made readable. Narrower band-pass filters are being used thus eliminating more extraneous energy from the record. Some companies are trying an overlap scheme whereby part of the output of each detector is fed into two or more recording channels. This reduces the number of independent traces on the record and consequently is felt by many to be undesirable, even though it does produce a better looking record.

Because of the better control of amplitude resulting from the use of automatic amplifiers, it has been possible to add additional traces to a given width paper. In the case of dip shooting where small increments of time are of such great importance, it is quite desirable to make all computations of dip from a single record. The standard of a decade ago was four to six traces on photographic paper or film four inches wide. Now as many as ten traces are put on the same width paper. At least one company had made arrangements to use as many as twenty traces on wider paper.

Changes in technique include the use of the highly argumentative multiple geophones and in a much closer spacing of data. Continuous profiling even in correlation areas is not uncommon. This is partly due to the fact that it is necessary to work in areas which are more difficult and complicated, both seismically and geologically.

Considerable progress has been made in solving the problem of severe weathering variations.

Large amounts of data on formation velocities have been obtained. In several states such as Kansas, Oklahoma and California this is done by cooperative organizations. Such information will be of great value in working out the detailed problems of the future.

Much more attention is being paid to the depth of shot holes and the formations in which to set off the charge. It was recognized in the very beginning of this work that exploding the charge in the natural water of the water table produced very much better results and in most areas this is still the best practice. In other areas it may be necessary to pick a rather precise depth for the charge. There has been a definite tendency for shot hole depths to increase.

Thus, while there has been enormous improvement in instruments and field technique in the past decade it would probably be fair to say that no changes of a fundamental nature have taken place. The one exception to this statement may be the Sonograph invented by Frank Rieber.[15,16] Here an entirely different type of oscillogram or

of the United Geophysical Company.

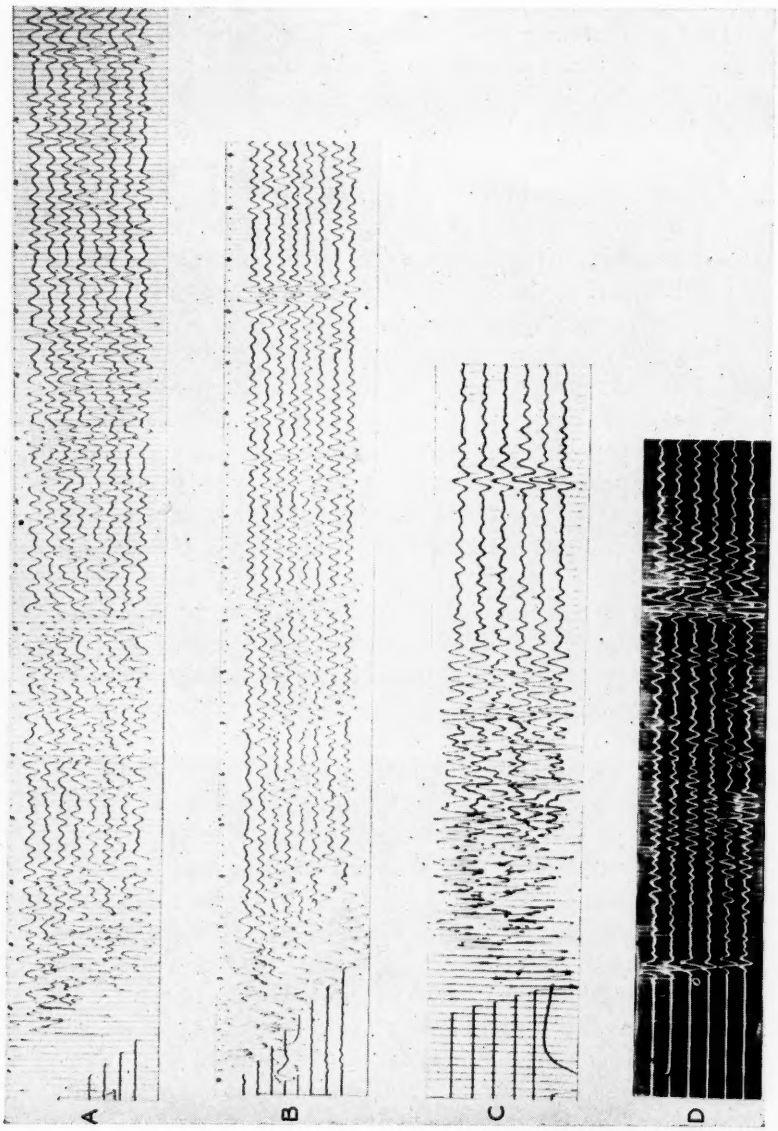

FIG. 2. REFLECTION RECORDS FROM FOREIGN COUNTRIES

A, Argentina; B, Java; C, Poland; D, Venezuela.

Records A, B, and C shown through the courtesy of the Seismograph Service Corporation, Tulsa, Oklahoma. Record D shown through the courtesy of the Geophysical Service Incorporated, Dallas, Texas.

record is made which is similar in principle to the sound tracks of the movies. The inventor claims distinct advantages in the analysis of such records.

The explosives companies have worked hard on the problems of turning out high explosives which are better adapted to our peculiar problems, and caps in which the difference in time between the fusing of the bridge wires and the detonation of the cap is reduced to a minimum.

Entire credit for developing the reflection method belongs in the United States. Years after reflection shooting was a working reality here, there was a complete failure to recognize it in Europe. A careful perusal of foreign seismic literature up to 1933 reveals only a few vague references to its possibilities and no expressions of its actuality. That America was far, far ahead in this field has been rather conclusively demonstrated by the number of American reflection crews which have been engaged in foreign work in such countries as Trinidad, Venezuela, Java, Rumania and Poland.

Approximately 200 million acres, an area larger than the whole state of Texas, have been shot and reshot in this country alone, and although the total number of crews is some twenty per cent below the 1937 high, there is still much work to be done. As time goes on and the amount of unexplored acreage grows less, and as the geophysical problems become more complicated, the inexorable law of diminishing returns will force a further reduction in seismic activity. However, new provinces will be opened up which can be surveyed by the reflection method. Recent examples are Illinois, Arkansas and Mississippi. A year ago there were only three crews in the last mentioned state. Today there are twenty-three. This will be repeated, and, combined with lease evaluation and improved methods for reworking old areas, will result in a substantial amount of activity for a long time to come.

The total cost of seismic exploration in this country has been betwen 175 and 200 million dollars. The program has resulted in the discovery of approximately five billion barrels of oil, more than a billion barrels of which have been produced to date, the remaining four being a part of our proven reserves. In addition there are a great number of undrilled structures, many of which will undoubtedly be productive. A tremendous amount of acreage has been condemned and the industry has been saved many expensive dry holes.

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A BRIEF HISTORY OF THE GRAVITY METHOD OF PROSPECTING FOR OIL*

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ABSTRACT

An historical outline of the development of the gravity method of prospecting is presented. While the very early gravity work with pendulum equipment was for geodetic purposes alone, the increased instrumental sensitivity made available with the development of the torsion balance by Eoetvoes (1888), led in 1915, to the first gravimetric survey for oil prospecting in the Egbell field, Czechoslovakia. The application of the method to prospecting in the United States started in 1924 with the discovery of the Nash dome in Coastal Texas by a torsion balance survey. The development and use of improved pendulum equipment is discussed and finally the recent marked increase in gravity work resulting from the introduction of the gravimeter about 1930 to 1935.

There does not appear to exist an adequate historical account which traces to its origins the gravitational techniques currently used in prospecting for oil. In the past few years the development of excellent gravimeters has led to a revival of interest in gravity surveys to the extent that the volume of such work is greater than ever before. A suitable historical background for this work may therefore be of current interest.

Our knowledge of gravity begins with Galileo (1561–1642), who discovered the laws of free fall and of pendular motion (1589). The unit in terms of which geophysicists express their gravity measurements is the "gal," so named after Galileo. To Newton (1642–1727) we owe the law of universal gravitation. It was Huyghens (1629–1695) who first used pendulums in clocks (1657). The realization that gravity varied over the surface of the earth followed from the observation, first reported without explanation by Richer in 1672, that clock rates vary when they are moved from place to place. Newton and Huyghens pointed out independently, and almost simultaneously, that the observed effect must be due to the departure of the earth from the spherical form. This focused attention on the relation between the space variations of gravity over the earth's surface and the shape of the earth, and this relationship has remained, until very recently, the primary motive in making gravity observations at points distributed over the surface of the earth.

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All early gravity measurements were made with the pendulum. Their object was to throw light on the shape of the earth. Bouguer (1698–1759) was probably the first to make pendulum observations for this purpose. His name is perpetuated in the Bouguer corrections and Bouguer anomalies with which all technicians who make gravity measurements deal. During the years 1735–1743 Bouguer headed a French expedition to Peru which had for its principal objective the measurement of arc. On this expedition he made the first use of the invariable pendulum idea and made the first relative gravity measurements.

Although relative gravity measurements were successfully made so early by Bouguer, most gravity observations during the next 150 years were made by the absolute method. The pendulums used were generally of one second period and they, and associated equipment, were cumbersome to use and to move from place to place. The acceptance of the relative method, therefore, awaited the development of more convenient equipment for its execution. This was provided by von Sterneck about 1887. By using half seconds' pendulums and other devices, he greatly improved portability and ease of manipulation, and the availability of this apparatus was no doubt chiefly responsible for the strong up-surge of interest in relative gravity measurements which followed.

About the same time (1888) von Eoetvoes was beginning his revolutionary work in developing the torsion balance which bears his name. Although he made occasional progress reports to the Hungarian Academy of Sciences, his work was relatively unknown until he summarized eight years of work in 1896 in Wiedemann's Annalen der Physik in a paper entitled "Investigations Concerning Gravitation and Earth Magnetism." This paper is now regarded as a classic. The torsion balance determines the horizontal gradient of gravity. From an appropriate series of torsion balance observations between two points, the gravity difference between these points can be derived. In subsequent work, Eoetvoes endeavored to demonstrate to his own satisfaction, and to his professional colleagues, the suitability of his instrument to secure gravity information equivalent to that obtained by the pendulum. He drew idealized geologic sections for two media and computed their gravity effect, using the result to illustrate the relative advantages of his instrument and the pendulum.

Although Eoetvoes actually cooperated with others in the use of his instrument for geological investigations, his viewpoint always

remained predominantly geodetic. It was de Boeckh, Director of the Geological Survey of Hungary, who followed the work of Eoetvoes and his associates closely and who appears to have been the first to recognize broadly, the possibilities of such measurements in prospecting for oil.

Apparently the first gravity survey motivated by practical needs in the oil industry was made by Fekette and Pekar using the Eoetvoes balance over the then, one-well oil field of Egbell in Czechoslovakia. The survey consisted of about 100 stations and was made in 1915 and 1916. H. de Boeckh[1] records that he asked Baron Eoetvoes to make these measurements. Other accounts[2] indicate that they were made in behalf of the D'Arcy Exploration Company, an affiliate of the Anglo-Persian (now Anglo-Iranian) Oil Company. The apparent conflict may be resolved if one assumes that the D'Arcy Exploration Company dealt with Eoetvoes through de Boeckh.

The Egbell survey was strikingly successful and the publication of its results was prompt.[3] The student of history may be inclined to wonder why the application to petroleum prospecting did not gain immediate momentum. It must be remembered, however, that the Egbell survey was made during the first World War and that the results were published by the technical press of the Central Powers. Under these circumstances, the dissemination of this information through the principal oil-producing countries of the world was bound to be slow.

The first gravity survey over a salt dome was made by Schweydar[4] in 1917 over the Hanigsen salt dome near Hanover, in North Germany. The survey was made with an Eoetvoes balance. Schweydar deduced from the survey a number of position and shape characteristics of this dome, beyond those already known from drilling, which were subsequently confirmed by results from later wells.

Other very early torsion balance geologic surveys were reported by Professor R. Schuman[5] of the Technishe Hochschule of Vienna and by Dr. H. Gornick.[6]

The first paper on the gravity method of prospecting to be published in the United States appeared in the October-November, 1923

[1] Mitteilungen aus dem Markscheidewesen, Freiberg 1920, p. 6.

[2] Oestereichische Monatschrift, Vol. 1, No. 5, August, 1920, pp. 208–211.

[3] Montanische Rundschau, June 1, 1923.

[4] Zeitschrift fuer Praktische Geologie 26, 1918, pp. 157–162.

[5] Oesterr. Berg u. Huettenmann, Nos. 69 & 70, 1921–1922.

[6] Verein Deutscher Eisenhuettenleute Erzausschus Bericht No. 2, Dec. 15, 1921.

number of "Economic Geology". Its author was Stephen Rybar[7] and its title "The Eoetvoes Torsion Balance and Its Application to the Finding of Mineral Deposits." The gravity surveys discussed in this paper had all been reported by Eoetvoes ten or more years earlier.

Evidently geological applications of gravity measurements first followed from the use of the torsion balance rather than of the older pendulum. To a large degree this was true because the torsion balance was more suitable for the mapping of small local gravity variations. The inherent necessity for the relatively close spacing of torsion balance stations was undoubtedly an important factor in attracting attention to their geological significance. The accuracy obtainable with pendulum equipment then available was insufficient for the purposes of local surveys.

Barton reports[8] that de Golyer made an unsuccessful attempt to secure an Eoetvoes balance in 1914. Two balances were imported to the United States by his organization in September or October, 1922 and two by Roxana Petroleum Corporation (Shell) in November or December of the same year.[9] Both organizations made their initial observations during the last week of 1922.

The first salt dome and oil structure discovered in the United States by any geophysical method[10] was the Nash dome in Brazoria County, Texas. It was discovered by torsion balance survey made by the Rycade Oil Corporation (Amerada subsidiary) early in the spring of 1924.

There followed immediately, an intensive campaign of torsion balance surveys which did not begin to taper off until the end of 1936. The amount of torsion balance work being done in this country today is negligible.

It must not be assumed, however, that the gravity pendulum and the geodesists who continued to use it were without influence on the development of the gravity method of prospecting. The work of Bouguer in Peru has already been referred to. His pendulum measurements there, at three stations, are of special interest to us. One was near sea level; another on a table land (Quito) at an approximate elevation of 9,400 ft. above sea level and the third on the summit of Mt. Pichincha at an elevation of 15,700 ft. In applying the Bouguer

[7] Economic Geology, Vol. 18, 1923, pp. 639–662.
[8] Bull. Amer. Assoc. Petroleum Geologists 9, 1925, pp. 612–613.
[9] Geophysical Prospecting, 1929, A.I.M.M.E., p. 275.
[10] Geophysical Prospecting, 1929, A.I.M.M.E., p. 444.

correction (allowance for mass between level of station and sea level), he obtained an unexpected anomalous result. It indicated that the mountain mass had much less gravity effect than would be expected from the visible mass and its known density. The effect was also confirmed by the corresponding measurements of the deflection of the vertical which he also made. Its cause was never understood by Bouguer.

When it later appeared that similar discrepancies were invariably encountered whenever gravity measurements were made on mountain masses, this anomalous condition attracted attention. More or less vague suggestions that the visible topography of mountains must be associated with substantial mass deficiencies underlying them were made before 1855, but they got nowhere until Airy and Pratt almost simultaneously in that year, dealt with these speculations in a quantitative way. They both postulated that the earth's crust may be considered divided into blocks of undefined horizontal extent and that these blocks are supported by a more or less fluid substratum. Pratt assumed that the subcrustal (sub-block) mass is in hydrostatic equilibrium and that all blocks have the same mass and are in contact with the substratum at the same level, the level of compensation. Since the blocks in areas of high mountains are longer, and the mass is postulated as equal for all blocks, it follows that the average density under mountains must be less than under lowlands and seas.

The Airy theory postulates that the blocks float in a fluid medium of greater density and are supported by buoyancy. The density of all blocks is substantially the same. Blocks involving high topography will therefore be heavier and extend further into the buoying medium. For this reason, Airy's is often referred to as the "roots of mountains theory." It appears that the term isostasy was first used by Dutton[11] (1889), who, unlike Airy and Pratt, was a geologist. Dutton's paper is lucidly written. He finds an isostatic condition necessary on purely geologic grounds and finds support for it in the elevation and depression of land masses undergoing erosion and deposition. He believes gravity measurements to be pertinent to geologic science and says that too few pendulum measurements exist for the wants of geologic science.

In 1912, appeared two Special Publications of the U. S. Coast and Geodetic Survey, Nos. 10 and 12, by Hayford and Bowie[12] and

[11] Dutton, C. E., Bull. Phil. Soc. of Washington, Vol. II, 1888–89.

[12] Hayford, J. F. and Bowie, Wm., "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," U.S.C.&G.S., Spec. Pub. No. 10, 1912.

by Bowie[13] respectively, both entitled, "Effect of Topography and Isostatic Compensation Upon the Intensity of Gravity." Here, apparently for the first time, the gravity stations were discussed with respect to their local geological environment. The geological literature of the years immediately following leaves no room to doubt that Bowie's papers[14] and his personal influence had made geologists gravity conscious. G. K. Gilbert[15] 1913 concluded that the contoured gravity anomaly map of the United States (219 stations) is in some way an expression of subterranean structure. In the same year J. W. Spencer[16] discussed the submarine canyons and valleys of the continental shelf along the Atlantic coast of the United States and the geology of the Great Lakes region in relation to the pertinent gravity data then available. In 1917 E. W. Shaw[17] outlined the basis for his belief that pendulum surveys should be useful in the search for hidden salt domes in Coastal Texas and Louisiana. David White's presidential address[18] to the Geological Society of America, December 27, 1923, was entitled "Gravity Observations from the Standpoint of Local Geology." It is of special interest that during the interval 1917–1923, numerous station sites suggested by him to the U. S. Coast and Geodetic Survey were located for the purpose of studying the relation between variation in gravity and the known local geologic structures.

Apparently pendulum equipment was first used commercially in prospecting by the Marland Oil Company in 1925 and 1926 in Kansas and north-central Oklahoma. The instruments first used duplicated the contemporary apparatus of the U. S. Coast and Geodetic Survey and were purchased from the Bausch & Lomb Company. It was soon realized that the equipment in hand afforded a precision of measurement which was just barely sufficient and that the facility of measurement needed to be substantially improved to meet the needs of prac-

[13] Bowie, Wm., "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," U.S.C.&G.S., Spec. Pub. No. 12, 1912.

[14] Bowie, Wm., "Investigations of Gravity and Isostasy," U.S.C.&G.S., Spec. Pub. No. 40, 1917.

[15] Gilbert, G. K., "Interpretation of Anomalies of Gravity," U.S.G.S., Professional Paper No. 85, 1913, pp. 29–37.

[16] Spencer, J. W., "Relationship Between Terrestrial Gravity and Observed Earth Movements in Eastern America," American Jour. of Sc., 4th Ser., Vol. 35, No. 210, June 1913, pp. 561–573.

[17] Shaw, E. W., "Possibility of Using Gravity Anomalies in the Search for Salt Dome Oil and Gas Pools." Science N.S.46, December 7, 1917, pp. 553–556.

[18] White, D., Bull. of the Geol. Soc. of America, Vol. 35, 1924, pp. 207–278.

tical prospecting requirements. A development program therefore seemed necessary and was undertaken promptly by Wyckoff and Eckhardt.

Wilsing[19] had in 1897 described a pendulum in the form of a circular disc with a co-axial eccentric circular hole. He showed mathematically how the position of the hole and the diameters of the two circles could be so chosen as to give the pendulum a minimum period with respect to secular changes of length and temperature variation. Wilsing's objective was the use of this type of pendulum in gravity measurements. His paper discloses no experimental work in that direction. In 1927 Schuler[20] devised a more conventional form of pendulum, satisfying a similar minimal condition, his objective being application to astronomical clocks. Meisser[21] was the first to describe gravity pendulum apparatus embodying the minimum period idea.

The minimum period property of a compound pendulum has been an old idea, well known for a long time. I remember deriving it as a problem in mechanics as a student prior to 1908. It is demonstrated by Messerschmidt in his book, "Gravity Determinations at the Earth's Surface," published in 1908. Under these circumstances it is difficult to understand why the obvious practical application to gravity-pendulums was so long delayed. At any rate, Wyckoff and Eckhardt devised minimum period pendulums of which the body was a fused quartz cylinder[22] of lenticular section and the head was made of Invar. A clamping arrangement controlled from the exterior was introduced. This overcame the need of opening the case and removing the pendulum when moving between station sites and removed numerous difficulties and inconveniences attending the removal of the pendulum from the case and its replacement. A further improvement was to use several identical pendulum units and to swing them simultaneously. Undoubtedly the greatest obstacle to the increase of precision of pendulum measurements has been the failure of the invariable pendulum to be invariable. This obstacle was minimized by designing for lowest available temperature coefficient (fused quartz), minimum period, short observation period (1 hour) and by adopting a method of operation which provides a frequent check on the period

[19] Wilsing, J., Zeitschr. fuer Instrumentenkonde 17, 1897, p. 109.

[20] Schuler, M., Zeitschr. fuer Phys. 42, pp. 547–554.

[21] Meisser, O., Zeitschr. fuer Geophys., 1930, pp. 1–12.

[22] These were secured from the General Electric Company and were the largest pieces of clear fused quartz they had made up to that time.

of the pendulum. This was done by keeping one pendulum always at a base station. The field pendulums were run at this base station at the beginning and end of each day's field operations. The invariability of the field pendulums was therefore controlled twice daily against the base pendulum which, because of lack of transportation and otherwise favorable operating circumstances at the base, was given the greatest possible opportunity to be invariable. The field and base pendulums were started simultaneously by radio control and the beginning and end of the period of observation determined by radio signals received and recorded at the base and field locations. The interval between the initial and final signal had to be sufficiently long to include an adequate number of swings of the pendulums but otherwise was arbitrary.

The design, construction and test of the revised equipment and technique occupied the remainder of 1926 and some of 1927. The experiments demonstrated that a substantial step in improving both the precision and facility of operation had been taken. In 1927 and 1928 a pendulum survey of substantial extent was made in an area in north-central Oklahoma where the structural situation was relatively well known. The results were decidedly encouraging.

In December 1928, Eckhardt and Wyckoff became associated with the newly-organized Research Department of the Gulf Oil Corporation. Here they were in a position to design new equipment based on their past experience. The pendulums were entirely of fused quartz, a monolith in structure except for a cylindrical plug on which the knife edge was ground. They were of the minimum period type and two pendulums were used in each case, swinging in opposite phase in the same plane to minimize the sway effect. This arrangement also served to minimize the effect of horizontal seismic disturbances. The external temperature of the case was thermostatically controlled. These features added to those previously embodied in the Marland apparatus achieved a very close approach to the desired precision.

Field operations with the Gulf pendulum equipment were started in Michigan in April, 1930. A survey of 63 stations was made over a period of about 5 months. The station output was small because the same stations were observed many times, since the primary object of the survey was to gain full information on the performance of the equipment. The pendulum party was transferred to central Oklahoma in September, 1930, where a survey of 178 stations was accomplished in the succeeding 6 months. The depression halted these operations and provided the opportunity for refining the equipment.

Pendulum operations were resumed in the Texas Gulf Coast in August, 1932 and were continued to June, 1936. During this period approximately 8500 pendulum stations were observed in Coastal Texas and Louisiana. This work led directly to the discovery of the Cleveland Oil Field in Liberty County, Texas. It also included the definition of the Tomball gravity anomaly by pendulum observations made on three successive days. No other geophysical method available at the time was capable of producing equally conclusive results in so short a time. The pendulum also produced a striking gravity picture of the Conroe dome which a very detailed torsion balance survey had failed to do because of the unusually severe near-surface irregularities prevalent there.

In 1927 Berroth[23] reported on a method of gravity measurement with pendulums which has many points of similarity with that just described. One pendulum unit remains continuously at a base station while a similar unit is moved about from one field station to another, starting at the base and returning there after a number of field observations. This procedure is referred to by Berroth as the "Referenz" method. The paper gives the results of 9 pendulum stations which were observed over the Oldau-Hambuehren salt dome. They were observed in 1925 and comparison is made with a torsion balance survey made in 1924. The agreement is reasonably good. Commercial application of the Referenz method devised by Berroth was made by Mintrop through the Seismos Gesellschaft. A contract was made with the Gulf Oil Corporation and operations were begun in Oklahoma in March, 1929. This operation initially resulted in 15 stations per month, which later was increased to 25 per month by the addition of a second field unit. Over a period of two years this operation resulted in the observation of 392 pendulum stations in Oklahoma and 89 in Texas and Louisiana.

Also in 1927, Heiland[24] described a procedure for speeding up and improving pendulum measurements which he considers an improvement over that of Berroth. He proposed the use of base and field pendulum units, as does Berroth, but suggests the use of photographic recording. Berroth was prevented from making his base and field observations precisely simultaneous because he retained the use of the flash-box (coincidence-apparatus). Heiland's scheme does offer a

[23] Berroth, A., Referenz Pendelmessungen am Salzhorst Oldau-Hambuehren.

[24] Heiland, C. A., "Suggestions for the Improvement of Pendulum Operations," Transactions, American Geophysical Union, 1927, pp. 66–71.

workable process but as far as is known, no experimental work was done to follow up his proposal.

It is understood that in 1932 the Humble Company purchased pendulum equipment from the Askania Company. They do not appear to have used it other than experimentally in the field.

It is well known to those who have dealt with the subject that at best pendulum operations are ponderous and require the constant exercise of operating skill and technical alertness. The success of such operations is dependent to an unusual degree on the training, experience and ingenuity of the operating personnel. Furthermore, while occasional special measurements could be made to 0.1 mg. or better, it was found that in routine measurements a probable error of 0.25 mg. represents an average result with the best of equipment. To practitioners of the gravity method of prospecting it was obvious that the achievement of a greater precision would have considerable practical value. Outstanding advantages of the pendulum method are its capacity to furnish a gravity picture of a sizable area more promptly than the torsion balance, and its insensitivity to local surface irregularities. These considerations led geophysicists to turn their attention to the development of gravity meters, or gravimeters, devices in which the gravitional pull on a mass is balanced against some form of elastic force. Many such instruments have been described.[25] We shall restrict our attention to those instruments which have found appreciable application in prospecting.

The earliest instrument of this type seems to be that of Threllfall and Pollock[26] (1899). The oldest instrument which has found use in prospecting is that of Ising (1918). Its use seems to have been largely restricted to the Scandinavian countries. In the United States gravimeter development appears to have been first undertaken by the Humble Oil and Refining Company. This development resulted in the Hartley,[27] Truman and later models. The first Humble-Truman

[25] The following papers are selected because they discuss a number of instruments and give references which provide convenient access to the related literature:

a. Ising, G., "Use of Astaticized Pendulums for Gravity Measurements," A.I.M.M.E. Tech. Pub. No. 828, 1937.

b. Graf, A., "Ein neuer Statischer Schweremesser zur Messung und Registrierung Lokaler und Zeitlicher Schwereaenderungen" Zeitschr. fuer Geophys. 14, 1938, pp. 152–172.

c. Heiland, C. A., Gravimeters, Etc. "A.I.M.M.E. Tech. Pub. No. 1049, 1939.

[26] Phil. Trans. 193 (1899), pp. 215–258.

[27] Hartley, K., PHYSICS 2 (1932), pp. 123–130.

meter was sent to the field in June, 1930. The development of the present Gulf gravimeter was initiated late in 1932 and the first instrument entered regular field service in early March, 1935. By the end of 1936 eight instruments were in the field, which number was substantially increased in 1937. Up to January 1, 1940, in excess of 200,000

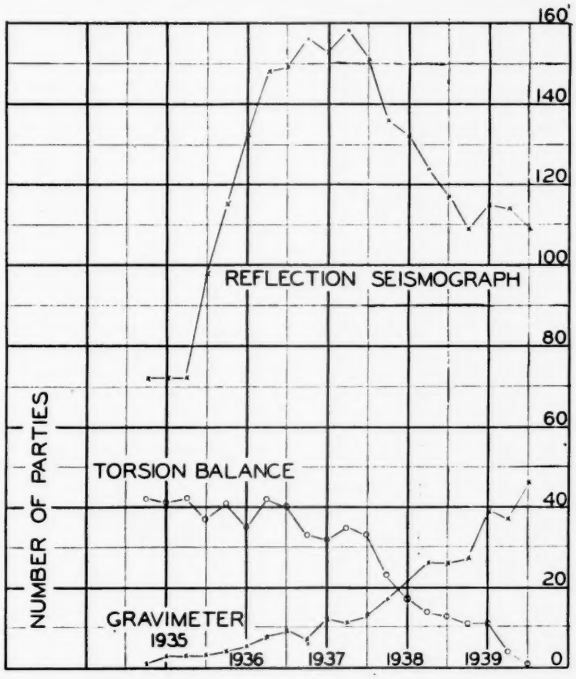

FIG. 1. Fluctuation of geophysical activity in states bordering Gulf of Mexico, by quarters, 1935–1939.

gravity stations have been observed by the use of Gulf gravimeters. The average monthly output per instrument has been over 400 stations, fluctuating widely with variations in the ease of getting around. The record output is 110 stations in a single 8-hour day. The probable error of a single observation has been determined by numerous field observations to be less than 0.05 mg. It is our opinion that this precision is all that can be practically utilized in all ordinary problems of gravity prospecting.

Similar data about other instruments would be of interest, but do not seem to be available.

The Hollweck-Lejay[28,29] inverted pendulum has been considerably used by Shell, as has the Thyssen[30] gravimeter. The Humble and Carter have made considerable use of the instrument developed by themselves. The Mott-Smith[31] gravimeter has been extensively used by Continental and others, and more recently Brown, Romberg, Kannenstine and Sweet have developed instruments and offered them for prospecting service.

Some statistics as to the fluctuation in geophysical activity may be of interest. The accompanying graph shows this over a period of five years down to date. The area to which these statistics apply was chosen because the best statistics were available for it. It accounts for at least three-quarters of the total activity in the United States. To expand these statistics to include all of the United States would have involved a considerable amount of labor which, in view of the unavoidable uncertainty of the result, was not deemed justified. The graph shows clearly the replacement of the torsion balance by the gravimeter. What is not apparent from the graph is that, while the total number of gravity parties of both kinds does not change much, the changeover really represents a substantial expansion of gravity work because a gravimeter party, day for day, covers very much more ground than a torsion balance party.

Adequate data as to what discoveries are to be credited to gravity prospecting are not available. That they are substantial cannot be doubted. It can now be reported that in the first half of 1937 a gravimeter survey made with two instruments yielded salt dome discoveries averaging one per week for a string of well over twenty. The cost of this entire campaign was less than the average cost of discovering a single salt dome by reconnaissance seismic surveys. The gravity method has a well-deserved place in geophysical prospecting. It has at times played a decisive role and it cannot, therefore, be safely ignored.

[28] Lejay, "Recherches sur les Pendules Elastiques," Bulletin Geodesique (1930).

[29] Holweck, F. et Lejay, P., Mesures Relatives de la Gravite au Moyan du Pendule Elastique Inverse July des Observateurs 17 (1934).

[30] v Thyssen, S., Zeitschr. fuer Geophys. 11 (1935), pp. 131, 212.

[31] Mott-Smith, L. M. and F. W., "Advancements in the Use of the Gravimeter in Oil Exploration," Petroleum Engineer, 10 (1939).

TYPICAL ELECTRICAL PROSPECTING METHODS*

W. M. RUST, JR.†

ABSTRACT

A very general review and discussion of electrical prospecting methods, particularly as applied to petroleum prospecting, is given. It is pointed out that while the electrical methods have not received the wide spread acceptance in this field that other methods enjoy, continued interest may well be justified. The opinion is expressed that the most optimistic sign of a brighter future for electrical prospecting for petroleum is the evidence being accumulated to support the theory of secondary effects in relatively shallow strata overlying deposits of oil and gas.

INTRODUCTION

Electrical prospecting methods occupy a unique position in the list of geophysical methods. From time to time for over a century they have aroused widespread interest and today most geophysical research groups are devoting a share of their efforts to the study of electrical methods. A study of various typical electrical methods will show that many of these have given excellent results in special cases and yet have met with little favor in more general situations.

Electrical methods tend to attract the attention of research men because they are familiar with electrical equipment and electrical concepts. Moreover, the range of the electrical properties, which are actually encountered in practical field work, is far greater than that in any other geophysical method. But the chief reason for the continued interest in electrical prospecting lies in the almost unbounded variety of substantially different modifications which are available.[1]

Methods have been tried which employ no current. Other methods employ direct current. Still others employ alternating currents with frequencies varying from a fraction of a cycle per second to many million cycles per second. Still others employ pulses varying from very slow pulses to very rapid transients. Each of these modifications gives results which in some areas are quite different from those given

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† Humble Oil & Refining Co., Houston, Tex.

[1] For a brief bibliography covering early references to various methods see "A Historical Review of Electrical Prospecting Methods," W. M. Rust, Jr., GEOPHYSICS, Vol. III (1938), pp. 1–6.

by others. Additional modifications are available in the manner in which the energy from the current is transmitted into the ground; it is possible to use electrodes, loops of wire insulated from the ground, plates or antennae. Similarly it is possible to measure potential, induced current, electromagnetic field strength, magnetic field, polarization and other results of the energization of the earth.

A brief study of some typical electrical methods may be useful to one having the problem of choosing a method suitable to some particular problem or may help in the task of devising a more useful modification.

NATURAL EARTH POTENTIALS

The earliest studies of the earth's electrical properties were Fox's measurements in 1830 of the potentials produced by the action of ground waters on copper ores in a Cornish mine. In this method no current is supplied to the ground, instead one merely measures the potentials which are already present. In many cases it is found that the positions of anomalous potentials correspond to the location of ore bodies. Since these potentials are usually rather small it is customary to employ so-called "reversible" or "non-polarizing" electrodes and a sensitive potentiometer. The normal field technique is to locate equipotential lines, either directly on the ground or by measuring potential difference at a network of stations and drawing contours.

This method has found widespread application in the search for metallic ores and in those special cases where it is applicable, it has met with remarkable commercial success. However, with the important exception of the somewhat analogous measurement made in electrical well-logging, this method has not and is not likely to find application in petroleum geophysics. This method is rather closely analogous to magnetic prospecting.

The familiar, though somewhat mysterious, large scale earth currents, which circulate in the earth's crust in a number of whorls which follow the sun, have from time to time been used for prospecting. Since the total amount of current can not vary greatly over large regions, it is obvious that abnormal distribution of resistivity or resistive layers will result in abnormal potentials. Thus, the equipment used in the previously prescribed method can be used to locate such anomalies. It is claimed that this method has been used successfully to locate faults. It has, however, the disadvantage of involving too many variables, but may in special cases prove valuable.

DIRECT CURRENT METHODS

The basic direct current method is the "equi-potential map" method in which current is passed into the ground through two groups of electrodes, which usually approximate point electrodes far apart or line electrodes somewhat closer together. It is customary to reverse the current periodically in order to avoid the effects of natural earth potentials and polarization. By the use of two exploring electrodes and a potentiometer, equipotential curves are located. By a comparison of these with the curves computed for a homogeneous subsurface, it is possible to locate compact bodies with resistivity different from the surrounding earth. In many cases, faults can be located. This method is somewhat analogous to gravitational prospecting but has the advantage of greater flexibility and the disadvantage of more rapid decrease of effect with depth.

A familiar modification of this method is the Gish-Rooney "apparent resistivity" method, in which the current and potential electrodes are equally spaced along a straight line, the potential electrodes being inside the current electrodes. The ratio of the potential across the potential electrodes to the current through the current electrodes is determined; this ratio is multiplied by a constant, depending on the electrode spacings, which would give the resistivity if the earth were homogeneous. The variation of this quantity, called "apparent resistivity" has been studied theoretically for many special cases. In practice, one of two variations is usually employed. In one, the spacing is kept constant and the entire equipment is shifted along the measuring line. This variation is suitable for finding faults and bodies whose resistivity is different from the surrounding earth. It also finds application in electrical well-logging. In the other variation, the center of the system is kept fixed and the electrode separation systematically increased. This variation is useful in determining vertical variations in resistivity and in locating large scale structures. Theoretically, this method offers the possibility of extending the investigation to any desired depth. In practice, however, lateral variations in resistivity, surface conditions, electrical disturbances and other factors seriously limit the accuracy obtainable and deep seated anomalies are likely to escape detection.

Numerous modifications of these methods have been proposed in an effort to avoid these difficulties. Typical of these are the "potential-drop ratio" methods. In these methods, instead of measuring the potential between two electrodes, the ratio of the potentials between two

pairs of electrodes at different distances from the current electrodes is measured. Alternatively, the ratio of the potentials produced between two electrodes due to current flowing between two sets of electrodes at different distances from the potential electrodes, is measured. This is said to reduce the effect of surface variations and correspondingly increase the effect of deep anomalies.

Another group of modifications, somewhat similar in principle but different in technique, are the profiling methods. Typical of these is the continuous profile method of Jakosky. In this method, the two potential electrodes are fixed in position as is one current electrode. The other current electrode is moved continuously along the profile and a curve showing the variation of the potential with the distance between current electrodes is plotted. This is repeated for other positions of the electrodes. A comparison of the resulting curves offers the possibility of distinguishing effects due to deep anomalies from shallow variations. In practice, the current is in the form of comparatively short pulses to avoid the difficulties with direct current, mentioned above. In one modification of the method, the magnetic field produced by the current is measured instead of the potential. In some areas, this method is reported to have given very accurate information concerning deep beds.

ALTERNATING CURRENT METHODS

When low frequency alternating currents are used, the methods are essentially the same as the corresponding direct current methods. Low frequency alternating currents have certain advantages over direct currents. Thus, there is no difficulty due to natural earth potentials or polarization. Another advantage is the possibility of amplifying the measured potentials with simple equipment. To offset these advantages, the current sources are less stable than batteries, and capacity and inductance effects cause some difficulties.

Analogous to the direct current measurements of apparent resistivity, are the alternating current measurements of "mutual impedance." In this method, current flows into the ground through two electrodes and by means of an amplifier and AC potentiometer the resulting potential across two other electrodes is measured. Both the amplitude and phase of the potential are of interest. This method offers the interesting possibility of varying the vertical distribution of current without moving the electrodes, simply by changing the frequency. It also offers a better sensitivity to the location of good con-

ductors below poor conductors. The most serious defects of this method at present are the unsatisfactory theory and the great importance of the position of the leads.

An important alternating current method is that practiced by Sundberg. In this method, alternating current of a moderately high frequency flows through a large loop of wire laid out on the ground. The phase, intensity and direction of the horizontal component of the resulting electromagnetic field are determined by a loop antenna and amplifier. The method is subject to modifications to meet local conditions and has achieved considerable success in Sweden in prospecting for ore. It has been applied in petroleum prospecting but did not meet with general approval.

RADIO MEASUREMENTS

Numerous experimenters, particularly in Germany, have been interested in the possibility of using radio waves in prospecting. Various modifications have been proposed which depend upon measuring the absorption of radio waves transmitted through the volume of earth to be tested, either by placing the transmitter and receiver in boreholes, or by reflecting the waves from subterranean conductors. This modification has been tried in locating water in desert areas. A variation of this method was recently tried on a commercial basis. This variation was supposed to locate deposits of hydrocarbons directly due to their anomalous absorption of certain specific high radio frequencies. Apparently the expected results were not achieved. A simple modification which several authors have reported as giving useful geological data, consists in making a radio field-strength survey of the area surrounding a broadcasting station. Commercially available field-strength measuring equipment in used and a map plotted showing the results of these measurements. Anomalous variations in these measurements are said to be correlatable with geological anomalies.

The usually accepted theory of the transmission of radio frequency energy, which has been fairly well substantiated by experiments, indicates that except in very arid regions the effective depth of penetration of radio waves is very small. At present, there is not available sufficient data to justify too optimistic a view of the radio methods.

TRANSIENT METHODS

Several modifications of the "Eltran" method have been described. These have in common, the use of a rapidly changing direct

current, which may be either a simple sharp change in magnitude of current, or a short, intense uni-directional pulse of current. In the usual applications, this current is led into the ground by one or more pairs of spaced electrodes, although the method could be applied by passing the current through a loop of wire. The current causes a potential to appear across two other electrodes. This potential may be recorded or some characteristic of its time-rate-of-change may be determined by use of a wave analyzer or a "dummy transient matching circuit" which is adjusted to give a transient which is very nearly equal to the earth transient.

The transient methods, theoretically, offer all the information which can be supplied by electrical methods if the various modifications of these methods, as regards electrode arrangements, quantity measured and so on, are employed. However, in spite of the rather remarkable results which in certain cases have been accredited to Eltran work, it has, in general, met no wider acceptance in petroleum prospecting than have the other electrical methods.

CONCLUSIONS

One is impressed by the contrast between the widespread acceptance of electrical prospecting methods in mineral prospecting and the almost complete lack of routine, commercial application of these methods in petroleum prospecting. The explanation of this difference doubtless lies in the difference between the problems encountered in the two fields.

The first striking difference lies in the respective relations of the resistivities of ores and oil sands to the surrounding materials. In the first instance there is a large variation, the resistivity of the ores being but a very small fraction of the resistivity of the imbedding earth, whereas, as electrical well-logs demonstrate, the resistivity of an oil sand is frequently not very much higher than that of the adjacent strata, nor is the resistivity of the salt water sand, which is frequently associated with the oil sand, much lower than that of the adjacent strata. Thus, the task of directly locating oil sands by electrical methods appears to be extremely difficult. Consequently, whereas in mineral prospecting one seeks them directly, in petroleum prospecting it is customary to seek the oil indirectly. This has usually resulted in a search for favorable structures.

The second striking difference one notes is that ore deposits of commercial value are usually relatively near the surface, and their

thickness is generally a fair fraction of their depth. On the contrary, an oil bearing structure may be many thousands of feet below the surface and yet be of great commercial value. Unfortunately, it is quite generally true that the influence of a structural anomaly upon electrical measurements falls off rather rapidly with depth, so that shallow variations may completely obscure the effects of deep structures.

Finally, the chief demand made upon mineral prospecting methods is a determination of the approximate areal extent of the ore deposit, whereas, it is customary to demand reasonably accurate information on the depth and closure of a prospective oil structure. This, unfortunately, is a demand which can rarely be met with an electrical method.

In spite of these difficulties, continued interest in electrical methods in petroleum prospecting may well be justified, for the theoretical linitations of electrical methods have not yet been sufficiently well-defined to enable one to say that no electrical method can find oil in place directly, or determine structural data quantitatively. At present, however, the most optimistic sign for a brighter future for electrical prospecting for petroleum, is the evidence which is accumulating to support the theory of secondary effects in the upper strata over a deposit of oil and gas.

FIFTEEN YEARS OF GEOPHYSICS: A CHAPTER IN THE EXPLORATION OF THE UNITED STATES AND CANADA, 1924–1939*

JAMES B. MACELWANE, S.J.†

Knowledge of geophysical methods of prospecting was not widely spread in America previous to 1924 and it was only late in that year that startling success in the discovery of oil-bearing structures began to be achieved by them. Hence we may say without exaggeration that a new era of geophysics began with the year 1924. As Barton[1] says:

In March 1924 the Nash salt-dome was discovered by the torsion-balance method; in October the Orchard dome was discovered by the seismic method, and the Long Point dome by the torsion-balance and seismic methods. The discovery of salt-domes in the Gulf Coast by ordinary methods of prospecting had become most difficult, and the current value of a new dome was between $500,000 and $1,000,000. The discovery of three salt-domes in relatively quick succession brought the technical value and commercial importance of the geophysical methods sharply to the attention of American oil companies. With the beginning of 1925, the use of the torsion-balance and seismic methods began to expand rapidly in America.

It was thought that stock might well be taken at this time of the sum total of coverage by various geophysical methods. It seemed to the writer that a series of maps, one for each of the major methods, would present the information to the best advantage.

The writer appealed to all of the commercial companies—both producing and consulting—for comprehensive data which would permit the construction of composite maps indicating the areas that have been explored by the several methods.

The years 1925–1929 constitute the era of whirlwind seismic refraction reconnaissance. This success with the refraction method was made possible by a rapid succession of improvements in equipment and methods. The mechanical seismograph was replaced by electromagnetic seismographs and the sound wave method of determining the

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† Director, Dept. of Geophysics, Saint Louis University, St. Louis, Mo.

[1] Barton, Donald C., "Petroleum Geophysics," *The Science of Petroleum*, Oxford University Press, p. 321.

time and the distance of the explosion was replaced by radio signals and precise surveying. The new techniques made it possible to cover not only dry land but marsh and coastal waters. By the beginning of 1929 when Heiland[2] published his monograph "Geophysical Methods of Prospecting" considerable areas had been explored by the seismic refraction method in Alabama, California, Kansas, Louisiana, Mississippi, New Mexico, Oklahoma, and Texas (see Fig. 1). It was the

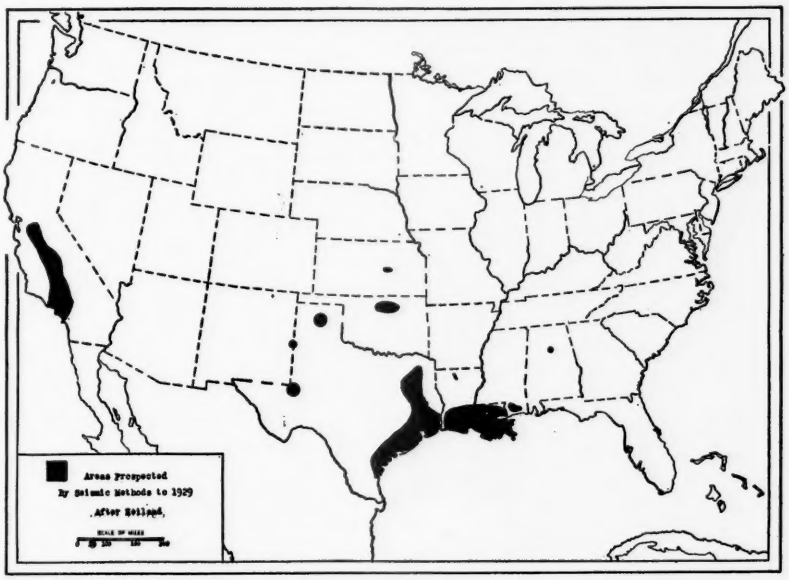

FIG. 1. Outline map after Heiland of the areas in the United States that had been prospected by the refraction method of seismic prospecting prior to 1929.

Geophysical Research Corporation which first made practical use of the electrical seismograph and it was the electrical type of pickup together with advances in communication engineering which made possible the modern multi-trace reflection seismograph whose development was also due largely to the Geophysical Research Corporation, although the method had been tried long previously by Karcher, Eckhardt and McCollom. In fact, McCollom obtained patents on the method which have proven fundamental.

[2] Heiland, C. A., "Geophysical Methods of Prospecting," Quarterly of the Colorado School of Mines, Vol. XXIV, No. 1, March, 1929.

The years 1929 to the present may be called the era of the reflection method which was at first used extensively in the Mid-Continent area of the United States. It was not until 1932 that its use became general in the Texas-Louisiana Gulf Coast. The seismic reflection method had been developed to a point where it is now second only to the drill in the precision with which it is able to determine depths and

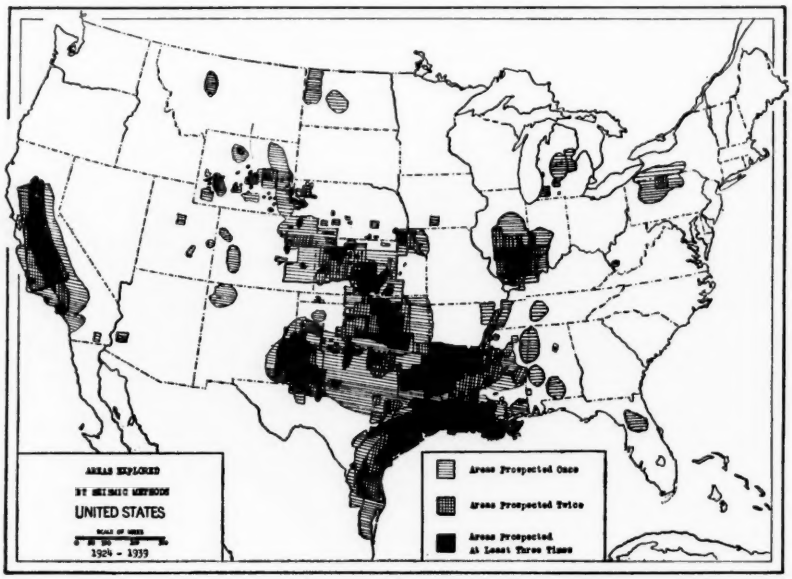

FIG. 2. Composite map of areas explored by seismic methods between 1924 and 1939.

outline structures. Ten years have, therefore, elapsed since the introduction of the reflection method.

Horizontal lines on the map shown in Fig. 2 indicate an area that was prospected at least once by seismic methods. The addition of vertical lines indicates one repetition. The solid black areas have been prospected at least three times. It will be seen that large areas were gone over by the seismograph time and again. In addition to the data obtained directly from the companies concerned some information from other reliable sources has been included. Nevertheless the map is somewhat incomplete because a very few of the companies found it impossible to cooperate; and the nature of many of the reports made separate mapping of the areas explored by the refraction and reflection methods impracticable.

The magnetic method was in extensive use in North America from 1927 onward. Its popularity was due in part to the relative inexpensiveness of the method and the rapidity with which areas could be covered. There was a deceptive semblance of simplicity in the observations made with the various types of magnetometers which was intriguing. As the years passed, however, the difficulties in the

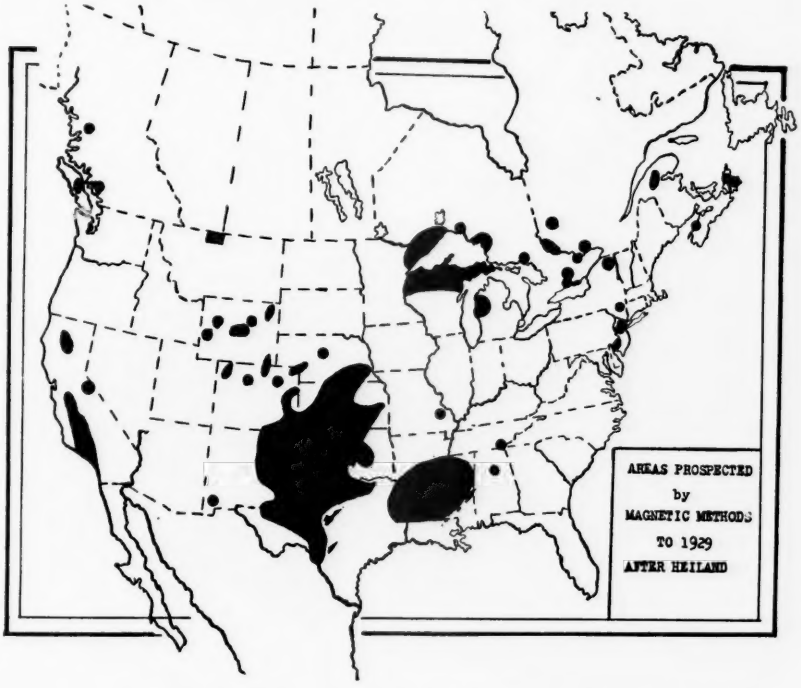

FIG. 3. Areas in the United States and Canada that had been explored by geomagnetic methods prior to 1929. After Heiland.

interpretation of magnetic data became more and more apparent until by 1931 the use of the magnetic method in petroleum prospecting had greatly decreased. But as a reconnaissance method in new areas it still has value. In the mining field its application has been practically continuous. As a result, in 1929 (see Fig. 3) Heiland could report detailed magnetometer surveys from Alabama, Arkansas, California, Colorado, Kansas, Louisiana, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, New Jersey, New Mexico, Okla-

homa, Tennessee, Texas, Wisconsin, and Wyoming. In Canada it had been used in the provinces of Quebec, Ontario, New Brunswick, Nova Scotia and British Columbia. On the present map (Fig. 4) there are added magnetic surveys in the states of Arizona, Florida, Georgia, Illinois, New Hampshire, New York, South Carolina, South Dakota and Utah.

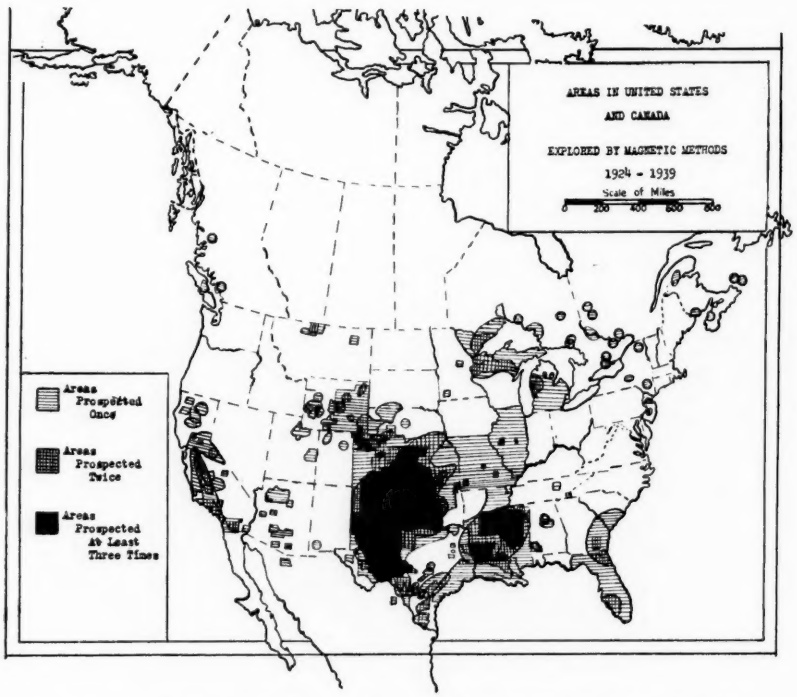

FIG. 4. Composite map of areas in the United States and Canada prospected by geomagnetic methods between 1924 and 1939.

In the application of the gravitational methods there are two main eras. The era of the torsion balance, 1924–1937 inclusive, and the era of the gravity meter, from 1938 to the present. The torsion balance had excellent success in the Gulf Coast from the start. By 1929, according to Heiland (see Fig. 5), torsion balance surveys had been conducted in Arkansas, Arizona, California, Colorado, Kansas, Louisiana, Michigan, Mississippi, Montana, New Mexico, Oklahoma, Texas and Wyoming and in the province of Ontario, Canada. However, its application had already reached its peak in 1931 and had

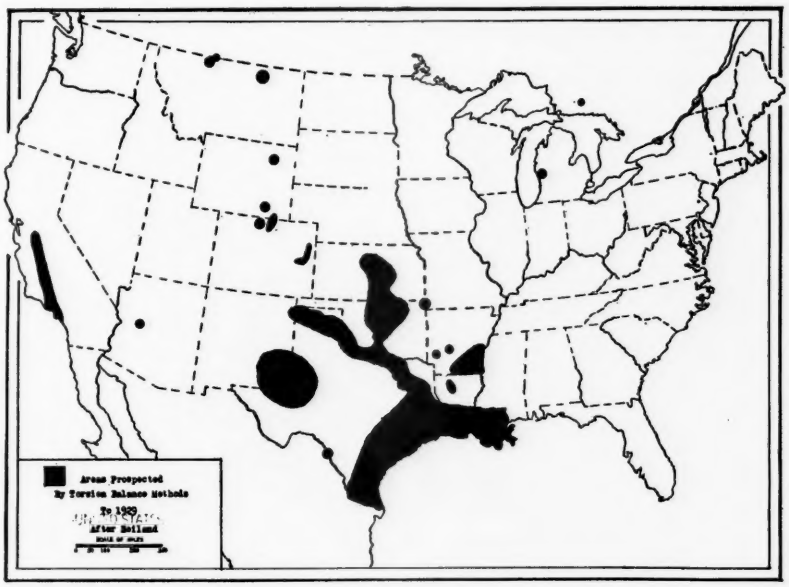

FIG. 5. Map after Heiland of the areas in the United States and Canada that had been prospected with the torsion balance prior to 1929.

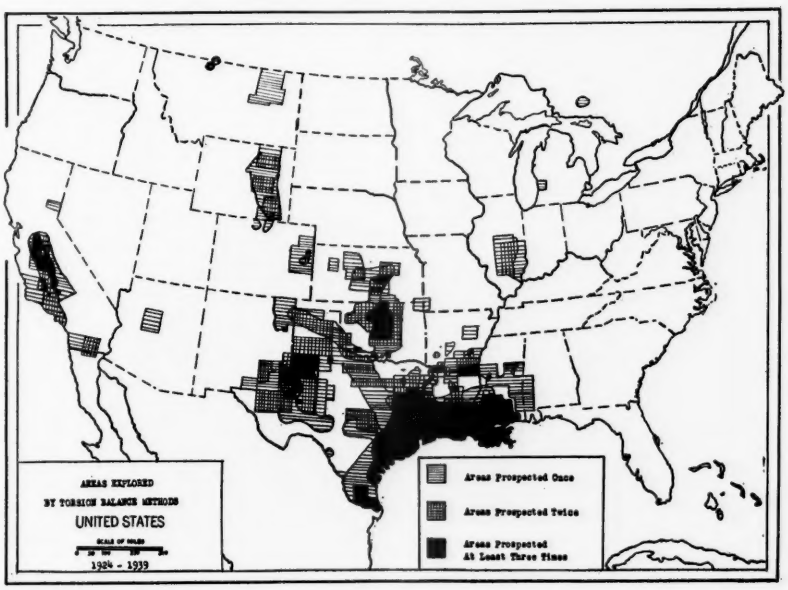

FIG. 6. Composite map of torsion balance surveys in the United States between 1924 and 1939.

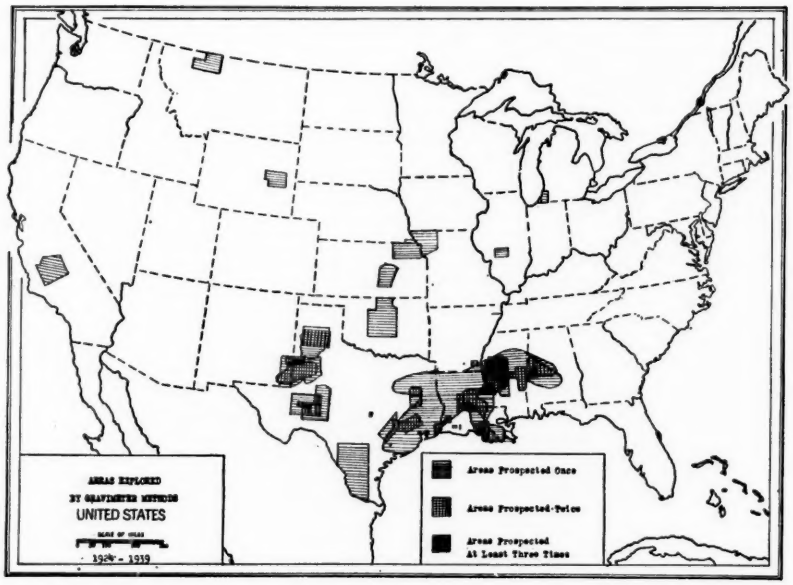

FIG. 7. Composite map of gravimeter surveys in the United States up to the end of the year 1939.

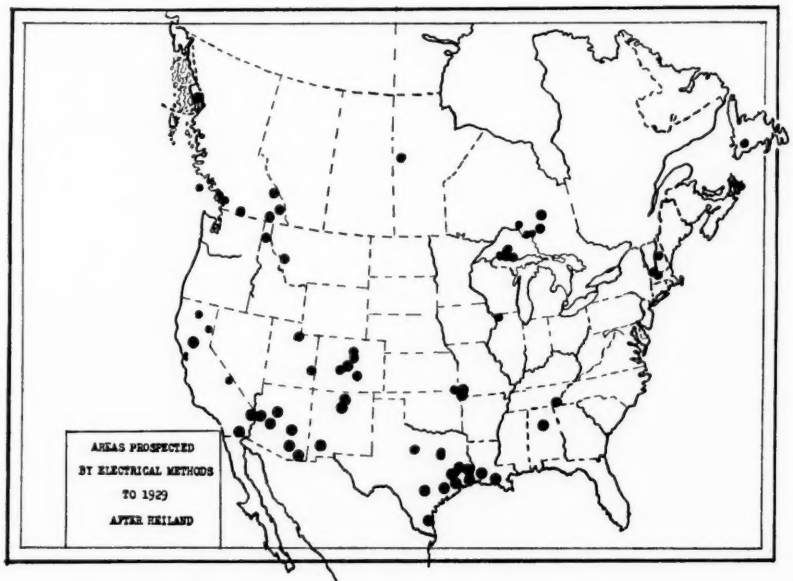

FIG. 8. Locations where electrical methods of prospecting had been applied prior to 1929. After Heiland.

begun a slow decline. Fig. 6 shows the areas explored with the torsion balance between 1924 and 1939. We are at present in the midst of a resurgence of gravity surveying beginning with the advent of field-worthy and sufficiently sensitive gravimeters in 1937–1938. In fact so rapidly may these surveys be conducted and so difficult and slow is the process of adequate interpretation of the data thus obtained that there has accumulated in the files of most companies an undi-

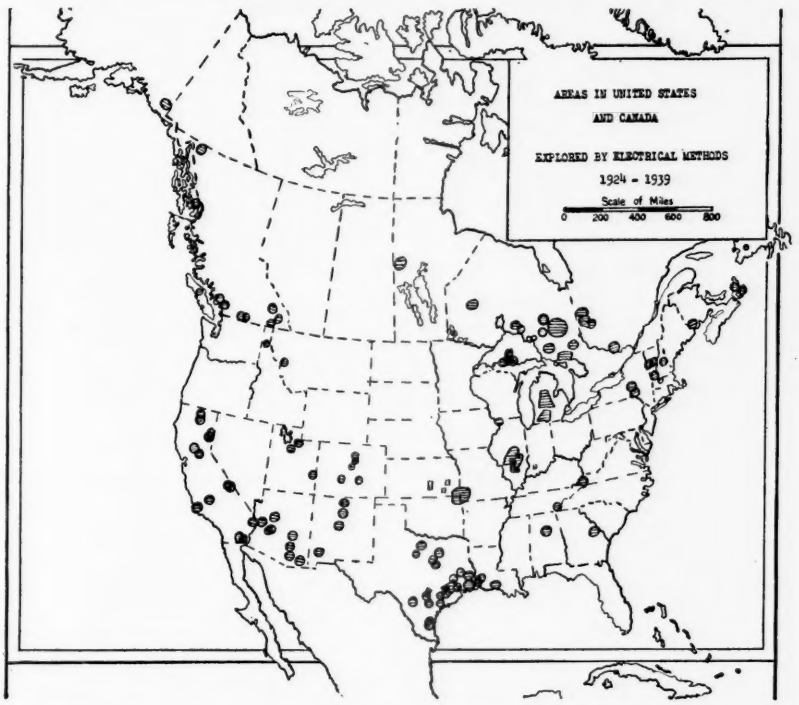

FIG. 9. Composite map of locations where electrical prospecting was done, 1924–1939.

gested mass of differential or relative gravity values whose meaning is not altogether clear. A separate map (Fig. 7) is presented to indicate the areas that have been prospected with the gravimeter up to the end of 1939.

The electrical methods have proven most useful in the mining field. They were found to be inferior to the seismic and gravity methods in prospecting for petroleum. Certain of the electrical methods are used in connection with geochemical prospecting because there would seem to be a connection between certain electrical anomalies and geochemical prospects. By 1929 (see Fig. 8) electrical methods

had been applied in Alaska, Alabama, Arizona, California, Colorado, Idaho, Illinois, Louisiana, Massachusetts, Michigan, Missouri, New Hampshire, New Mexico, Tennessee, Texas, Utah and Vermont and in the Canadian provinces of British Columbia, Manitoba, Nova Scotia, Ontario and Quebec, as well as in New Foundland. Since that time these methods have been applied in Georgia, New York, Oklahoma, and in the Province of New Brunswick. It is probable that this map is even less complete than those prepared for the other methods.

In closing the writer wishes to express his thanks for the generous cooperation of the administrative officers and of the geologists and geophysicsts of the commercial companies whose contributions of pertinent data have made this survey possible. The writer received a few communications, which were couched in too general terms for mapping purposes, for example, stating merely the states in some part or parts of which work had been done. Thus one company reported work in mining exploration by electrical methods in Arizona, California, Colorado, Idaho, New Mexico, and Texas and in petroleum exploration by electrical methods in Arkansas, Mississippi, Oklahoma and Texas without giving any indication of the approximate location of the work.

A PERSPECTIVE OF EXPLORATION FOR PETROLEUM*

E. E. ROSAIRE†

ABSTRACT

The first petroleum prospecting technique, based on the recognition of visible seeps of oil and gas, was rational and direct. The exhaustive application of megascopic geochemical prospecting led to diminishing returns, and a period of rule-o'-thumb prospecting ensued.

Geological prospecting appeared on the scene, and, as a result, the anticlinal theory was evolved, to become a bone of contention for years within that profession. Eventually, however, the anticlinal theory was accepted by petroleum geologists, and so structural prospecting developed.

The exhaustive application of structural prospecting by geological methods led to the discovery of many oil fields, but, eventually, diminishing returns ensued. A period of pessimism as to the nation's reserve followed, as rule-o'-thumb prospecting became the only possible prospecting procedure.

Geophysical prospecting appeared on the scene in 1923, and was successful in the solution of a highly specialized problem without reliance upon depth estimations. With the passage of time, geophysical prospecting took on a structural complexion, and with the development of the reflection seismograph, a renaissance in structural prospecting took place.

The geophysical phase of structural prospecting opened the vast basins for prospecting, and so revolutionized exploration for petroleum. However, geological prospecting did not experience a similar renaissance.

Structural prospecting, in both its geological and geophysical phases, has been a rational but indirect prospecting method. Outstandingly successful, its exhaustive application is leading to diminishing returns. However, it has imposed a specialization upon both geological and geophysical prospecting which has stifled the natural development of geochemical prospecting from geological prospecting, has directed geophysical prospecting into an unduly narrow path, and, in permitting prospecting to greater depths, has resulted in an *impasse* wherein its success involves capital investments with prohibitive payouts.

Though tacitly neglected in the past, there exists a geochemistry of a petroleum deposit, depending primarily upon the effects of the slow effusion of hydrocarbons through the sedimentary environment of the petroleum deposit throughout geologic time.

Geochemical prospecting depends upon the chemical and physical measurement of one or more of the geochemical manifestations of a petroleum deposit, and the interpretation of the resulting data in terms of the local geology. Since structure is a necessary but not a sufficient condition for the accumulation of petroleum, geochemical prospecting is a rational and direct approach to exploration for petroleum, and in its turn will revolutionize prospecting to at least the extents that geological and geophysical prospecting did in the phases of structural prospecting which they initiated.

THE FIRST EXPLORATION TECHNIQUE—MEGASCOPIC GEOCHEMICAL PROSPECTING, RATIONAL AND DIRECT

The Drake well probably initiated organized prospecting for petroleum in the form of choosing well sites located in close proximity

* Presented at the Annual Meeting, Chicago, April 9, 1940.

† Subterrex, 701 Waugh Drive, Houston, Texas.

to visible seepages of oil and gas. *Megascopic geochemical prospecting* was quite rational in its obviously direct approach and for awhile played an important part in the discovery of oil fields. DeGolyer[1] has said that this first rational and direct approach is to be credited with the discovery of more petroleum than any other exploration technique used to date.

Setting the pattern for all subsequently successful exploration techniques, the continued application of this first prospecting method eventually resulted in diminishing returns.

The period immediately following was one of rule-o'-thumb prospecting, when well sites were chosen because the associated topography bore a resemblance, real or imaginary, to other well sites where production had been discovered.

THE SECOND EXPLORATION TECHNIQUE—STRUCTURAL PROSPECTING, RATIONAL BUT INDIRECT

Structural prospecting is divided naturally into two major phases, geological and geophysical, and has dominated petroleum exploration for several decades. Structural prospecting was born of and rose and fell with geological prospecting. However, structural prospecting outlived geological prospecting, undergoing a renaissance as soon as the subsequently born geophysical prospecting was found adaptable to the search for buried structure.

In its two major phases, structural prospecting has led to the discovery of an appreciable part of our past and present production. The writer would be the last to decry such an outstanding successful approach, certainly not as long as it was effective. However, faced by its diminishing returns, and seen in perspective, structural prospecting imposed a specialization which was not an unmitigated blessing. Such a conclusion is obvious when we consider the history of geological and geophysical prospecting in the light of subsequent events.

GEOLOGICAL PROSPECTING

It was no more than natural that geologists should have taken an early interest in the occurrences of natural oil and gas. J. V. Howell[2]

[1] E. DeGolyer, "Future Position of Petroleum Geology in the Oil Industry." Presented April 10, 1940, Annual Meeting, A.A.P.G., Chicago, Illinois.

[2] J. V. Howell, "Historical Development of the Structural Theory of Accumulation of Oil and Gas," pp. 1–33, Problems of Petroleum Geology. A Symposium A.A.P.G. 1934.

has traced that early interest, and has shown how the idea of structural prospecting evolved from the anticlinal theory and the associated hypothesis of the gravitational separation of gas, oil, and water in a common reservoir.

Although a born of contention within the geological profession for years, the introduction and specialization upon the anticlinal theory made possible a return to rational prospecting. That approach was indirect, for the objective was a trap within which an accumulation of petroleum might exist, not, as was the earlier objective, evidence of the deposit itself.

Structural prospecting by means of surface and near-surface geological exploration has led to the discovery of less petroleum[3] than did the first rational and direct approach, megascopic geochemical prospecting. During the geological phase of structural prospecting, however, the discoveries usually were located some distance from the markets, for the centers of population tend to be located where the featureless surface reduces the effectiveness of surface and near-surface geological prospecting. In those days, as earlier, "oil was where we found it."

On a world-wide scale, exhaustive geological prospecting led eventually to diminishing returns; a period marked by pessimistic predictions as to the imminent exhaustion of the nation's reserves, by a scramble for shale oil reserves, by the acquisition of the Bergius process for the hydrogenation of coal, and by consideration of the possibilities of lubrication through the use of colloidal graphite suspended in water. The price of crude oil rose to precipitous heights, and a period of random wildcatting ensued[4] when, once again, rule-o'-thumb prospecting prevailed.

GEOPHYSICAL PROSPECTING

Geophysical prospecting appeared on the scene in 1923, and was early successful in the solution of a localized geological problem, the location of the buried salt plugs of the Gulf Coast Embayment. Interestingly enough, the first successful geophysical techniques were not basically structural, for data from gravity and refraction fan determinations are two dimensional, and, in themselves, do not admit of depth predictions.

[3] E. DeGolyer, *op. cit.*

[4] W. F. Henniger, "Geology of Salt Dome Oil Fields," DeGolyer et. al., A.A.P.G. 1926, p. 776.

Actually, the refraction seismograph was introduced as a structural prospecting technique, but failed to justify that promise in its early trials in Mexico, Oklahoma, and the Gulf Coast. The technique did not become workable[5] until L. P. Garrett invented the tactics of refraction "fan" exploration, prospecting in only two dimensions.

However, as these techniques in their turn displayed diminishing returns, structural prospecting by geophysical methods slowly appeared on the scene. Gravity and refraction profiles were used to make depth estimations, and finally, a new geophysical technique was developed in the reflection seismograph, a method which was a "natural" for depth predictions.

Forthwith, a pronounced renaissance took place in structural prospecting. For the first time, the vast geologic basins were opened to structural prospecting, and the rate of discovery climbed.

The revolution effected by the geophysical phase of structural prospecting is illustrated by the production history of the Illinois Coal Basin. In 1905, the application of megascopic geochemical prospecting and random drilling in the Illinois Basin resulted in a rapid rise in production for that state to 28,000,000 barrels a year, about one-fifth of the nation's then current production. As the exploration cycle ran its course for these two forms of prospecting, the law of diminishing returns naturally ensued, as is shown by the resulting decline of Illinois production until, in 1934, the annual production was only 5,000,000 barrels. The pessimism then existing in prospecting circles is evidenced by the following quotation, circa 1930.

> . . . Twenty years ago, this petroliferous province accounted for approximately 20 per cent of all the oil produced in the United States. Thereafter, with the opening up of prolific areas in the Mid-continent fields and in California, the importance of the province became subordinate. In 1929, about 6,000,000 barrels were produced out of a total of over 800,000,000 barrels for the nation, thus representing about 1 per cent. During the years from 1889 to date, so many scattered wells have been drilled in the Eastern Interior Coal Basin Province that no hope remains for any large virgin pools . . .[6]

Following the introduction of geophysical prospecting, the annual production rose from 4,500,000 barrels in 1936, to 28,000,000 barrels

[5] E. L. DeGolyer, "Notes on the Early History of Applied Geophysics in the Petroleum Industry," pp. 1–10. The Journal of the Society of Petroleum Geophysicists, Vol. VI, No. 1, July, 1935.

[6] W. A. Ver Wiebe, p. 133, *Oil Fields in the United States*. McGraw-Hill Book Company, Inc., 1930.

in 1938, and to 90,729,000 barrels in 1939, with the peak not yet passed.

Elsewhere, this revolution in prospecting led to the practical abandonment of many areas previously favored because of their

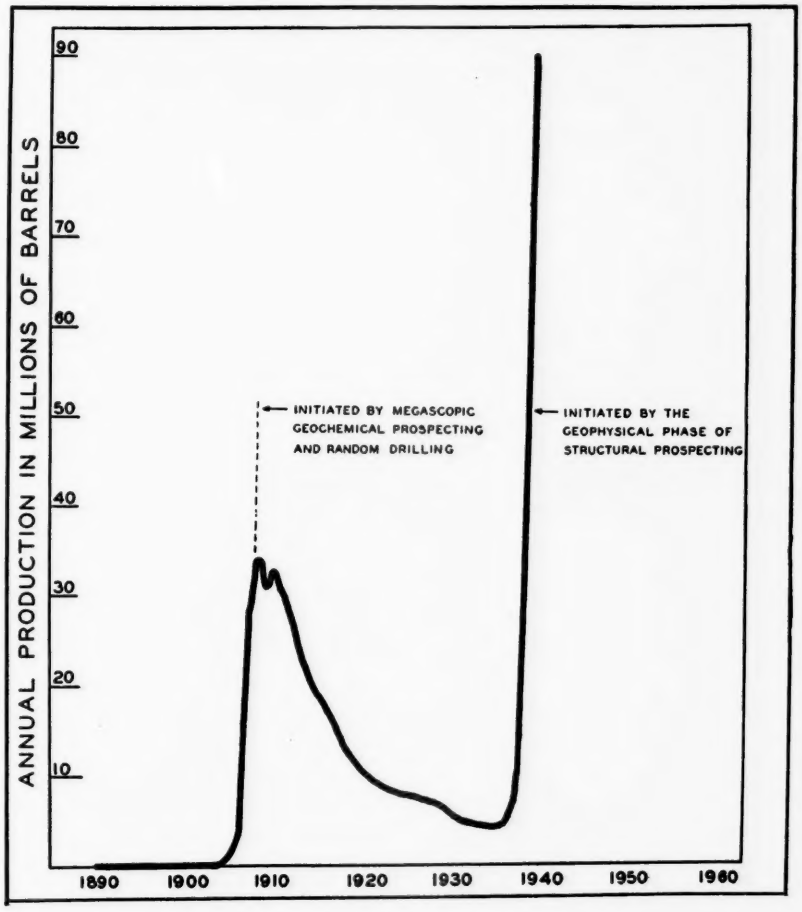

FIG. 1. Petroleum Production in the Illinois Basin.

earlier association with geological prospecting. As an example, the Rocky Mountain Province practically was abandoned in favor of the Gulf Coast and the Illinois Basin. The prospecting outlook was changed from "oil is where we find it" to "find oil where we need it most."

In spite of this striking renaissance effected by the geophysical phase of structural prospecting, signs of diminishing returns eventually appeared in the exploration picture. Once more a note of pessimism was sounded in the literature. directed this time, not at the magnitude of undiscovered reserves, but at the limited possibilities inherent in prospecting itself. One such said:—

> . . . We have all, therefore, drifted along from one structure finding method to another, until now we are approaching, apparently the real danger of an oversupply of methods and an undersupply of anticlines.
>
> . . . But, if we are to depend on folding alone, our future discoveries are indeed limited, for we are undoubtedly running low on the supply of untested domes and anticlines. . . .
>
> Since the search for domes, anticlines, and similar types of local deformation has been our chief method of attacking the problem of oil discovery, and if we are approaching the end of our supply of such structures, for the very reason that we are rapidly exhausting our finding methods down to the lowest depths at which we can drill oil, then what of the future? Where are we to find this billion barrels of new oil per year which all observers seem to think the nation will require for many years to come? The oil industry is not interested in our contours, in our gravity maxima and minima, in our rock velocities, our theories; it is interested in us only insofar as we can tell where to drill to find barrels of oil. It is our job to find this oil and, if we fail, the industry will find someone else to do it . . . .[7]

In view of the continued mass application of the reflection seismograph, that quotation certainly is even more pertinent today than when stated by Mr. Levorsen four years ago. We have increased our rate of structure discovery, but, on the other hand, Nature shows no inclination to follow suit in the rate of structure evolution.

THE EXISTING SITUATION

Today, once again, the prospecting cycle has run its course. For the year 1939 in the Gulf Coast, the rate of discovery has dropped back to that of 1936; the reflection exploration cost per discovery has increased to six times that of 1930;[8] and it is a matter of general comment that the one 1939 discovery of probable importance (Paradis) stands out against a background of discoveries in which the dry holes generally outnumber the producers. In the Mid-continent, an interval

[7] A. I. Levorsen, "Stratigraphic Versus Structural Accumulation." A.A.P.G., Vol. 20, Number 5, May, 1936, pp. 521–530.

[8] See Appendix.

of two years ensued between the last two major strikes in Oklahoma; the recent Pure Oil Company discovery in southern Oklahoma, and the discovery of the Ramsey Oil Field, in April, 1938.

The Moloch of mass exploration by the reflection seismograph requires new areas and new depths to maintain itself. We witness an areal extension into central Mississippi, a morsel which will not satisfy that god for long. There yet remains the Gulf of Mexico, where more structures can be found, but only by the solution of the unique legal and exploitation problems involved.

The ensuing vertical extension in exploration is of more immediate interest. Production has been established already at depths down to below 13,000 feet. Today, consideration is given to drilling wells to 15,000 feet. The associated rock pressures raise new production problems, which in their solution require experimental apparatus operating under pressures of 7,500 pounds per square inch. Recently, plans[9] were described which involved building such experimental apparatus for operation at 10,000 pounds per square inch, to aid in the solution of production problems already confronting the petroleum engineer. Meantime, the per-well production falls, and the executives reduce exploration budgets because of the enormous postponement of payout of the investment involved in the deep wells which they must drill because of the success of their programs of structural prospecting.

All this in spite of the very obvious fact that the shallow sand lens and other stratigraphic possibilities have been barely scratched in Oklahoma, Texas, and Louisiana, at a time when low-cost shallow wells usually are given higher allowables than those given the high-cost deeper wells.

Discovery is becoming more difficult and more costly in most of our major producing provinces, and in the present twilight of structural prospecting, we are forced into the consideration of marginally low-relief structures and stratigraphic traps. The rational basis of structural prospecting is no longer the shining rainbow, at the foot of which we may find the proverbial pot of gold (or, more practically, the barrel of oil). As happened once before, we have exhausted the reasonable possibilities of a rational prospecting approach, and in a headlong and unseeing fashion, have reverted to rule-o'-thumb prospecting.

Today, wildcat wells are located because individuals, and organi-

[9] E. O. Bennett, "Trends and Observations in Pressure Maintenance Practise." Presented February 13, 1940, A.I.M.E. Annual Meeting, New York, N. Y.

zations as well, persist in their "belief" in the effectiveness of established exploration methods, an opinion formed because of their past successes, and in spite of their recent failures.

They "believe" in reflection "highs," in spite of the numerous cemeteries of blasted hopes, among which are Iowa Colony, South Crowley, Fresno, and others; all demonstrations of the limitation recognized long ago by I. C. White,[10] that structure, even if present, is only a necessary and not a sufficient condition for petroleum accumulation.

Others "believe" in gravity minima, once significant in their indication of piercement type salt plugs, and which now are "believed" to be still significant in their indication of deep seated low relief structures, in blithe disregard of the Law of Inverse Squares.

THE RETURN TO RATIONAL PROSPECTING

GEOCHEMICAL PROSPECTING, RATIONAL, AND AGAIN DIRECT

In view of the quite obvious reversion to a state of chaos similar to that which existed prior to the introduction of rational exploration by geological prospecting, and again prior to the introduction of geophysical prospecting, we should give consideration to the possibility of measuring properties of a petroleum accumulation which, properly recognized and measured, may be more obvious now than the necessarily marginal geometry characteristic of the greater number of the remaining undiscovered structures.

The mining geologist would consider himself seriously handicapped were his interest and study arbitrarily restricted to the *geology* of an ore deposit, for its geochemistry is required in the solution of the problems with which he is confronted.

Yet, in exploration for petroleum, we tacitly consider a petroleum depost as an inert and static mass, similar to a coal seam. Such a viewpoint is furthered by consideration of a stripper field, where work must be done to extract the petroleum from its reservoir. However, a different perspective is forced upon one who observes or attempts to control a "wild" well, which handles tons of rock and water as a masker does confetti at Mardi Gras, and which bends and twists alloy steel as a child does warm taffy.

Granting the relatively impermeable nature of the shales and limestones of the typical sedimentary column, still, under the existing

[10] J. V. Howell, *op. cit.*

rock pressures and concentration gradients, one can hardly conceive that any such formation is *absolutely* impervious. Under pressure, hydrogen diffuses through a steel bomb. One is forced to consider than, that in the case of a petroleum accumulation under typical rock pressures, *some* effusion of hydrocarbons must take place into and through even a relatively impervious sedimentary environment. The amount and the rate actually are of secondary importance, for over the tremendous span of geologic time, the geochemical effects of slowly but incessantly effusing hydrocarbons have added up to totals of more than appreciable magnitude.

Scattered through the literature and through individual experience there are many instances, previously unrelated, which can be recognized now as geochemical manifestations of a petroleum deposit. Recent investigations and research have discovered other phenomena which are truly part of the geochemistry of a petroleum deposit. Other related phenomena remain to be discovered in this relatively new field of endeavor, which, in fact, is like a newly opened mine, for the investigator can hardly turn around without striking pay dirt. Unfortunately that condition has led to a great deal of confusion in the field, for new phenomena and brash hypotheses have been given undue importance, just as in a mine, a promising "color" may lead the miner temporarily astray from the pursuit of the primary vein.

These geochemical data require that their interpretation be geologically sound, for the forms that they take are closely related to the geological history of the area involved, and to the amount of petroleum accumulated. It is inevitable that our prospecting will undergo a great improvement, for, with a better understanding of the way in which the petroleum deposit affects the geochemistry of its sedimentary environment, our prospecting again will become rational. We will no longer need to "believe" in the effectiveness of a method which, successful in indicating gravity minima over piercement type salt domes, now is used because it indicates localized gravity minima where no piercement type salt domes exist.

We are now in position to recognize the adverse consequences of the specialization which the anticlinal theory imposed, first, on geological prospecting, and, second, on geophysical prospecting. We should be less ready to condemn Leslie[11] for his opposition to the anticlinal theory, which has had to be modified and extended more than materially in order to be as widely applicable as it now is. It is more

[11] J. V. Howell, *op. cit.*

than probable that Leslie recognized therein a specialization which usually is inadvisable in the early development of any science or technique.

Geological prospecting, which had originated and had fallen with structural prospecting, did not experience the renaissance that structural prospecting did with the advent of geophysical prospecting. The geologist reverted to a staff position, to guide and direct exploration, but, in the field proper, generally occupied the relatively subordinate position of surveyor.

It is interesting to note, however, that the pristine vitality of geological prospecting began to assert itself before the first decline of structural prospecting. To the geologist, chemistry is a natural second step to take in the search of data outside the field of descriptive geology. And so, circa 1920, we note the first steps towards *microscopic geochemical prospecting* in the Gulf Coast, where the orthodox structural approach of geological prospecting was not applicable. The work of H. E. Minor,[12] of the Gulf, on the geochemistry of Gulf Coast ground waters, probably represented the first attempts in that direction. His 1924 data, on the salinity of shallow ground waters, showed the presence and areal extent of what we now know as the Tom Ball oil field, a deep seated, low relief, Gulf Coast oil field. But the spectre of structural prospecting reared its ugly head, and Minor's data were not accepted because they were two dimensional, and showed no evidence of structure. Had geophysical prospecting been introduced five years later than it was, it is more than probable that geochemical prospecting would have developed into the successor of structural prospecting. That sequence would have been a natural course of events as shown by the parallel development in mining exploration. The mining geologist would consider himself arbitrarily handicapped were he required to restrict his interest and investigations to the geology of an ore body, for its geochemistry is required in the solution of the problem of its origin.

We see, then, that geological prospecting became completely subordinated to its brainchild structural prospecting. That offspring absorbed not only its parent, but arose to engulf another development, geophysical prospecting. Further, the normal development of geochemical prospecting from geological prospecting was stifled at birth,

[12] H. E. Minor, "Oil Field Waters of the Gulf Coastal Plain," pp. 841–905, Problems of Petroleum Geology. A Symposium A.A.P.G., Tulsa, 1934.

for the infant could not stand the rigors of exposure imposed by the existing specialization in structural prospecting.

In his turn, too, the geophysicist became obsessed with the shining rainbow of structural prospecting, and came to consider the reflection seismograph as the *ne plus ultra* of geophysical techniques. That limitation in viewpoint took place in spite of the fact that the geophysicist first won his spurs as a result of prospecting successfully in but two, not three, dimensions.

As a most significant sequence of attitudes, it is of the greatest interest to note that a geologist, Levorsen, called attention to the diminishing returns in structural prospecting, and pointed to the untapped possibilities in stratigraphic prospecting, in his inspiring presidential address before the A.A.P.G. in April, 1936. Levorsen[13] pointed out the dangers in continuing specialization in structural prospecting, using the striking analogy of well-armed hunters who persisted in going after rapidly vanishing small game in the same area where the poorly equipped natives brought in elephants with surprising regularity. Then, three years later, in 1939, Kannenstine, the president of this Society, indicated[14] that structural prospecting was of such vital importance in exploration geophysics that one should hesitate to compare the importance of the reflection seismograph with anything less impregnable than the Mannerheim Line. This is not the first time in history that the convert has become the zealot and fanatic of an old-time religion.

To keep the record straight, however, at the same time that Levorsen was calling attention to the disadvantages accruing from specialization in structural prospecting, the first paper on the Eltran[15] was delivered before this Society.

Three points of view developed as to that paper. To some of us, the Eltran was another although novel way of finding an oil field without mapping the associated structure; a new variation on the originally successful approach in exploration geophysics. To Dr. L. W. Blau* and his co-workers, that paper was a natural evolution in a

[13] A. I. Levorsen, *op. cit.*

[14] F. M. Kannenstine, "The Relationship of Geophysics to Geology," pp. 149–154, GEOPHYSICS, Vol. IV, No. 3, July, 1939.

[15] L. Statham, "Electrical Transients in Geophysical Prospecting," GEOPHYSICS, June, 1936, Vol. I, No. 2, pp. 271–277.

* Chief, Geophysics Research, Humble Oil & Refining Co., Houston, Tex.

rational program which typifies Geophysics; the orderly measurement of the properties of the sedimentary environment of a petroleum deposit. To the third group, largest of all, the phenomena were extremely heretical, in that they violated the canons of the rediscovered orthodoxy, structural prospecting. From that time through the present, this Society has witnessed contention between the prospecting and scientific attitudes on one hand, and the orthodox attitude on the other hand.

We face a new era, that of geochemical prospecting, in which the primary objective is the petroleum deposit itself. The former objective becomes of secondary importance, for, early in the evolution of structural prospecting, I. C. White recognized that structure was a necessary but not a sufficient condition for the existence of a petroleum deposit.[16] History repeats itself, for in from 1923 to 1930, the orthodox geologist looked askance at geophysical methods, with which was not *en rapport.* Today, the orthodox geophysicist looks askance at geochemical methods, which he cannot fit to his recently acquired structural fetishes, and so, in their violation of his canons of orthodoxy, he rejects them as taboo.

Neither is this situation new. In an entirely unrelated field of endeavor, the following quotation was made, by another student who had barked his shins on a similar orthodoxy.

> It is then particularly in the field of naval strategy that the teachings of the past have a value which is in no degree lessened . . . The unresting progress of mankind causes continual change in the weapons; and with that must come a continual change in the manner of fighting,—in the handling of troops or ships on the battlefield . . . The battles of the past succeeded or failed according as they were fought in conformity with the principles of war; and the seaman who carefully studies the causes of success or failure will not only detect and gradually assimilate these principles, but will also acquire increased aptitude in applying them to the tactical use of the ships and weapons of his own day. He will observe also that changes of tactics have not only taken place after changes in weapons, which necessarily is the case, but that the interval between such changes has been unduly long. This doubtless arises from the fact that an improvement in weapons is due to the energy of one or two men, while changes in tactics have to overcome the inertia of a conservative class; but it is a great evil. It can be remedied only by a candid recognition of each change, by careful study of the powers and limitations of the new ship or weapon, and by a consequent adaptation of the method of

[16] J. V. Howell, *op. cit.*

using it to the qualities it possesses, which will constitute its tactics. History shows that it is vain to hope that military men generally will be at the pains to do this, but the one who does will go into battle with a great advantage,—a lesson in itself of no mean value.[17]

That quotation is from Mahan's "The Influence of Sea Power upon History," published in 1896. Perhaps it was too much to hope for that the orthodox geophysicist of today would react differently than the orthodox geologist did in 1923, or the orthodox naval officer had in 1890. To what extent will history further repeat itself in this Society, now that geochemical prospecting bids for *lebensraum*, and challenges the decades old domination of structural prospecting, so recently rediscovered by the geophysicist?

APPENDIX

Investigation showed that, on the average, a two year lag intervenes, in the Gulf Coast between discovery by the reflection seismograph and discovery by the drill. Thus, in this regional study of discovery costs, the discoveries made by the drill in 1939 are to be credited to the reflection seismograph exploration of 1937. This consideration leads to the following table.

TABLE 1

Year of Discovery by the Drill	*Discoveries*	*Credit to Reflection Exploration for Year*	*Reflection Crew Years that Year*	*Crew Years per Discovery*	*Est. Cost per Crew Year*	*Exploration Cost per Discovery*
1932	2	1930	1.0	0.5	$ 80,000	$ 40,000
1933	2	1931	1.6	0.8	80,000	64,000
1934	9	1932	10.1	1.1	80,000	88,000
1935	12	1933	26.6	2.2	85,000	187,000
1936	20	1934	32.6	1.6	90,000	144,000
1937	34	1935	42.3	1.2	99,000	104,000
1938	29	1936	56.9	2.0	100,000	200,000
1939	23	1937	59.6	2.5	105,000	262,000

These data supplement those previously published,[18] with information as to the discoveries for 1938 and 1939 supplied by Mr. O. L. Brace.

[17] A. T. Mahan, *The Influence of Sea Power upon History, 1660–1783*, pp. 9–10. Little, Brown and Company, 1896.

[18] E. E. Rosaire. "The Paradox of Exploration." World Petroleum, Oct. 1938, pp. 38–42.

WELL LOGGING BY RADIOACTIVITY*

W. G. GREEN† AND R. E. FEARON†

ABSTRACT

A discussion of the relation of radioactivity curves to physical properties of strata studied, including the influence of the history of the rocks involved. Comparisons are made between the probable areal extent of correlatable horizons in various types of formations, and the ability of various logging methods to distinguish these layers is considered as an index of the geological usefulness of the various logging methods. The possibility of distinguishing altered zones which do not show marked physical differences fom the neighboring rocks (such as faults and unconformities), is discussed, and its bearing on the usefulness of radioactivity logging is considered. Illustrations of the correlating power of radioactivity logs are given. Comparisons with electrical logs and with geological sample logs are shown to illustrate the points discussed. A brief discussion of the development of the radioactivity logging method and of the technique of carrying out field operations is also given.

Well logging by one means or another has been practiced for many years. Its best known form is the sampling commonly done by geologists, who gather up samples of the cuttings of rocks penetrated and plot them on a strip of paper with relation to the depth at which they occur in the hole. In recent years, various characteristics of the rocks such as electrical resistivity, porosity of strata, drilling rate, etc., have been examined and plotted graphically with respect to depth.

There are, naturally, many properties of rocks which can be studied or measured and which could, in the case of a drilled hole, be plotted with respect to the depth at which they occurred in the hole. Among these properties are hardness, porosity, density, color, crystalline structure, content, electrical resistivity, and radioactivity.

Inasmuch as in the practice of geophysical well logging it is hoped to avoid the necessity for bringing actual samples to the surface, some of these properties may not be directly examined. Therefore, of these properties only a very few would have outstanding value as a geological tool. A desirable parameter should have as many as possible of the following properties:

1) Permanence with respect to time, the drilling process, etc.,
2) Significant relationship to lithologic characteristics of rocks,
3) Many vertical variations, providing to a high degree, ability to differentiate strata,

* Presented at the Annual Meeting, Chicago, April 11, 1940.

† Well Surveys, Inc., Tulsa, Okla.

4) Ability to work inside casing,
5) A great persistence of vertical variations laterally, providing good correlative qualities,
6) As direct a relation to the occurrence of oil (or other desired substances) as possible.

Standard literature discloses that radioactivity well logging must possess the first of these properties. Whether or not radioactivity logging can tell anything about fluid content, however, remains a doubtful question, on which as yet, there is not much evidence. The other properties mentioned, radioactivity logs appear to possess to a high degree. A discussion of these properties will be taken up in detail in this paper.

FACTORS AFFECTING RADIOACTIVITY OF SEDIMENTARY ROCKS

In the last several years, it has become generally known that all substances contain some radioactive material. This material occurred originally in the primary or igneous rocks. During the processes of erosion and redistribution of these rock fragments and debris, we find this radioactive material widely scattered in the sedimentary beds and in the waters of the oceans.

The amount of radioactive material deposited in the sediment is affected by two factors: First, the nature of fragments and debris of primary rocks redeposited as sediments and second, the remains of small organisms living in the ocean which may be contained in the sediments. It is probable that the first of these factors determines the radioactivity of conglomerates and sandstones, while the second factor undoubtedly influences the radioactivity of shales. Ordinarily, the radioactivity measurable in a sedimentary bed is not as large as the radioactive level in the primary rock. This is due to weathering influences, and to contamination and dilution. In some shale beds, however, it is possible that the level of radioactivity might be higher than it was in the primary rocks.

It is believed that certain micro-organisms of the ocean have an ability to concentrate radioactive elements. Radioactivity plays an important role in all biological processes, and the low radioactive content of sea waters is sometimes attributed to the fact that these living organisms have removed radioactive elements from the salts dissolved in the sea waters and have concentrated and redeposited these radioactive elements in their bodies which are buried in the sediments on the bottom of the sea.

It might, therefore, be said that it is impossible to predict beforehand the amount of radioactivity that may be measured in a certain section of a drill hole in a hitherto unfamiliar area. In general, we would expect the radioactive level to be higher in shale than in limestone or sandstone. Certain limestones being formed by the precipitation of pure calcium carbonate might not contain much radioactive substance. Other limestones having been deposited more slowly and contaminated by shale deposition and weathering influences, leaching, etc., might have more or less radioactivity. However, in the field work that has been done thus far, it has become evident that the levels of radioactivity encountered in a particular section, whether it be limestone, sandstone, or shale, carry over a considerable area, as far as a particular horizon is concerned.

FUNDAMENTALS OF RADIOACTIVITY

Perhaps by now you will have begun to wonder what radioactivity is. The property of radioactivity was so named because the chief evidence of its existence was a production of radiations.

In 1896 Henri Becquerel observed that certain salts of uranium gave off radiations which produced an image on a photographic plate even though the plate was protected by tinfoil or black paper. This effect was first very mystifying but it provoked a great deal of interest and stimulated a program of scientific research which has never been equalled. In extremely rapid succession various new elements were discovered which possessed this property of emitting unusual radiations; the radiations were studied and classified and the nature of their origin was fully established. As a result of this radioactivity research, which is still going on rapidly even at the present day, scientists have been able to formulate very precise ideas as to the nature and ultimate structure of matter and the alchemist's dream of the ages, the transmutation of elements, has been established as a fact. By means of the modern methods available in present-day physical laboratories, it is not only possible to observe the transmutations of the elements which go on spontaneously among the approximately 38 naturally radioactive elements, but to produce transmutations of kinds not heretofore imagined.

The interpretation of known radioactivity phenomena is changing rapidly as would be the case in any field on which a great deal of research is being done and the number of radioactive bodies available for study is increasing constantly. In spite of all this, however, there

are certain fundamentals of the subject of radioactivity which are extremely well known and almost universally accepted. One of these is the fact that all the effects of radioactivity are a direct consequence of the transmutation of the atoms of the element involved. Such transmutations occur by the loss of one or more of the simple particles of matter (such as electrons, protons, positrons, and helium nuclei) from the atoms of the substances which exhibit radioactive properties. Early in the history of the study of radioactivity the distinct natures of the several kinds of radiations were recognized. It has been demonstrated that alpha rays consist of rapidly moving helium nuclei, that beta rays are merely rapidly moving electrons, and that gamma rays are made up of radiations entirely similar to ordinary light but of very short wave length and therefore, capable of penetrating many substances ordinarily considered opaque.

In the beginning, the measurement and observation of gamma rays was rather more difficult than was the determination of the other radiations. As techniques of amplifying electrical currents became more and more developed it became much easier to observe and measure gamma radiations. At the present time the measurement of the gamma rays is the recognized standard method for determining the strength of all radioactive substances. Naturally, therefore, in these laboratories, the development of a device for radioactivity well logging was based entirely on the method of measuring gamma radiation, particularly so, in view of that fact that when this type of measurement is used, a log can be made inside of a casing. In fact so penetrating are the short wave length components of gamma radiations from most minerals, that logs can easily be made through two or three strings of casing of such thickness as is commonly used.

DETECTION AND MEASUREMENT OF GAMMA RAYS

A commonly used apparatus for measuring gamma rays is an ionization chamber. This device consists of a cylinder containing an inert gas and insulated electrodes connected externally to an electrical circuit. Since the gas is non-conductive, no current flows under ordinary conditions. However, if the cylinder containing the gas is placed in the vicinity of radioactive material, some of the gamma rays emitted therefrom penetrate the cylinder and pass through the gas. If a quantum or particle of radiated energy (sometimes called a photon) of this radiation accidentally is absorbed by one of the atoms of the gas, electrons will be emitted with a relatively large energy and are, there-

fore, able to produce many other ions by striking gas molecules and by ejecting particles from the walls of the chamber. The total number of electron charges which gamma rays produce in the gas is far greater than the number of photons absorbed. Thus the ionization of a gas by gamma rays is, to a great extent, an indirect process. Due to the ionization of the gas, an electrical current will be able to flow between the electrodes in the ionization chamber. This current will be directly proportional to the amount of ionization or to the number of photons absorbed in the gas in the ionization chamber. Since the radiation of gamma rays from a radioactive substance continues uniformly for very long periods of time, the current between the electrodes in the ionization chamber would be constant, except for statistical fluctuations, as long as it was kept in the same vicinity. If it were placed in an area where there was greater radioactivity, a larger current would pass. Conversely, in an area of less radioactivity, a smaller current would pass. With suitable auxiliary measuring equipment, it is possible to indicate the passage of gamma rays through the ionization chamber on an electrical indicator or meter. Likewise, it is possible to record it with some sort of graphic recorder.

In practice, it is possible to separate the ionization chamber quite a long distance from the recording apparatus if suitable amplifiers and transmission lines are provided. It is therefore possible to lower an ionization chamber into a bore hole and record continuously at the surface, the levels of radioactivity encountered at different depths within the bore hole.

RELATION OF RADIOACTIVITY TO OTHER PHYSICAL PROPERTIES OF ROCK STRATA

The relations which exist between a gamma ray log and the physical properties of the strata involved are a direct consequence of the orderly nature of the processes by which the strata were produced. It seems likely that certain conditions of sedimentation were accompanied either by high or low rates of deposition of radioactive substances, and that this was habitually true over considerable periods of time within sufficiently restricted areas. It is apparent, therefore, that a reasonable procedure to apply in attempting to interpret a radioactivity log in a particular field or area would consist in establishing empirically some generalities regarding the radioactivity of the rocks of the lithologic types encountered in the particular field.

Fig. 1 shows the application of the above described procedure to a

well in the Scholem Alechem Field, Oklahoma. It will be noted that in this example, shales have the highest radioactivity and sand and limestone are represented by minima. It should also be pointed out that sandy shales in some instances on this log show minima which are quite as pronounced as though due to definite sands. This is but another illustration of the fact that it is dangerous to assume too close a relation to exist between entirely different properties. Only with the greatest caution should generalities be arrived at or employed in unknown areas.

HISTORICAL GEOLOGY

It is possible that detailed studies of radioactivity curves may open up new avenues of approach to various questions of historical geology, particularly as regards the movement of subterranean waters, and their chemical characteristics. It has been noted that numberous black shales, particularly those of Lower Mississippian age, show excesses of radioactivity over other shales, something which will be more completely discussed in the next paragraph. The wide-spread occurrence of such black shales, and the fact that they are practically always strongly carbonaceous, suggests that some marine organisms existed which were able to concentrate radioactive substances in their bodies. Analyses of present marine plants, and of the media in which they live, have already confirmed the above idea. Another use of radioactivity logging in the study of historical geology from a scientific standpoint, would be in the identification and correlation of layers which show no fossils. Some clues as to the proper correlation of various layers within such formations might easily be obtained, which could be obtained by no other means whatever. Such a formation is the Frio of

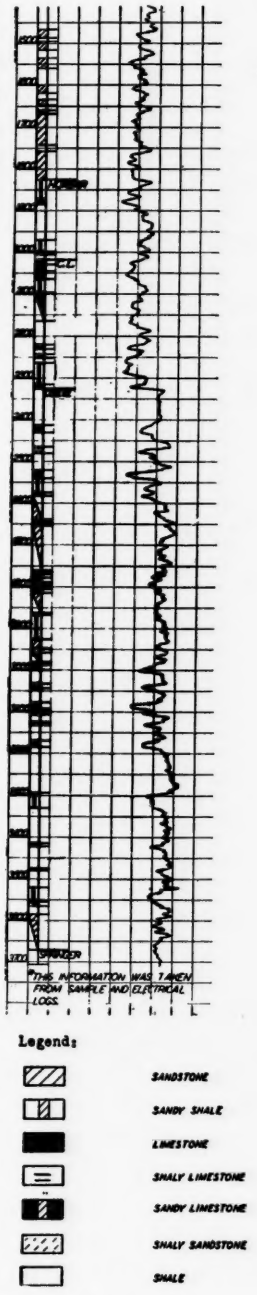

FIG. 1

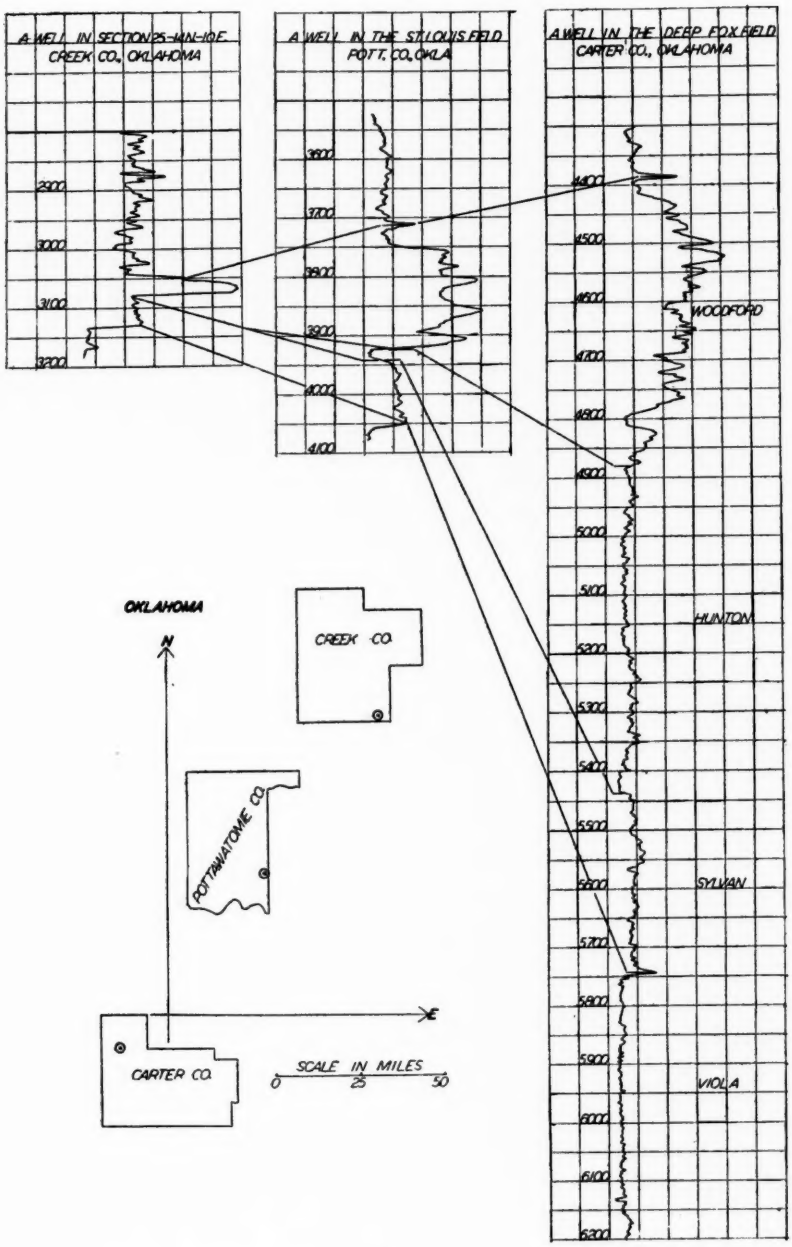
A WELL IN SECTION 25-WN-10E.
CREEK CO., OKLAHOMA
2900
3000
3100
3200
A WELL IN THE ST. LOUIS FIELD
POTT. CO., OKLA.
3600
3700
3800
3900
4000
4100
A WELL IN THE DEEP FOX FIELD
CARTER CO., OKLAHOMA
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100
6200
WOODFORD
HUNTON
SYLVAN
VIOLA
OKLAHOMA
N
E
CREEK CO.
POTTAWATOME CO.
CARTER CO.
SCALE IN MILES
0
25
50

FIG. 2

the Gulf Coast. It is also conceivable that some information bearing on the age or origin of cap rock on salt domes might be obtained.

CORRELATABILITY

The correlatability of any particular kind of well logging measurement depends upon the natural difficulties of correlation, imposed by geological factors, and upon the characteristics of the particular measurement. It is a fact of great use to geologists that some factors accompanying the deposition of sediments must have been vastly more extensive than others. One of the most extensive identifying qualities of a rock is the kind of fossils it contains. A formation may vary from sand to shale or to limestone as we cross a basin, but the fossil content will prove that it was deposited at the same time. Obviously, gross physical parameters, such as permeability, porosity, density, etc., are far from being the best for long distance correlations. Obviously, too, no geophysical method of well logging could observe and identify fossil content. Since most of the physical parameters of a stratum are subject to large regional variations, it is desirable to find one which is as little affected by regional changes as possible, if long distance correlations are to be made. The evidence is, as yet, quite fragmentary, but it strongly indicates that the gamma ray method of radioactivity logging may prove to be better than any other method for tracing the continuity of strata over long distances. A factor which no doubt influences the correlatability of radioactivity logs is the fact that very definite contrasts can be observed in shales, something to which electrical logs are poorly adapted. It is very likely that, in fields where sands lens in and out, better correlation points could be found in the shales. The fact that shales were made from finer sediments, carred far out to sea makes it seem reasonable that they would be more continuous than porous layers, produced from relatively narrow and rapidly moving beaches, river bottoms, etc. In Fig. 2 is shown a gamma ray cross section from Creek to Carter Counties, Oklahoma. The rapid southward thickening of all the formations is very evident, and a significant feature is the manner in which the Chattanooga-Woodford formation maintains its high degree of radioactivity in spite of its marked lithologic change from shale to chert towards the south.

Gamma ray radioactivity logs offer, for the first time, the possibility of locating a fault, or an unconformity, in a particular well, without reference to other wells. An unconformity, for instance

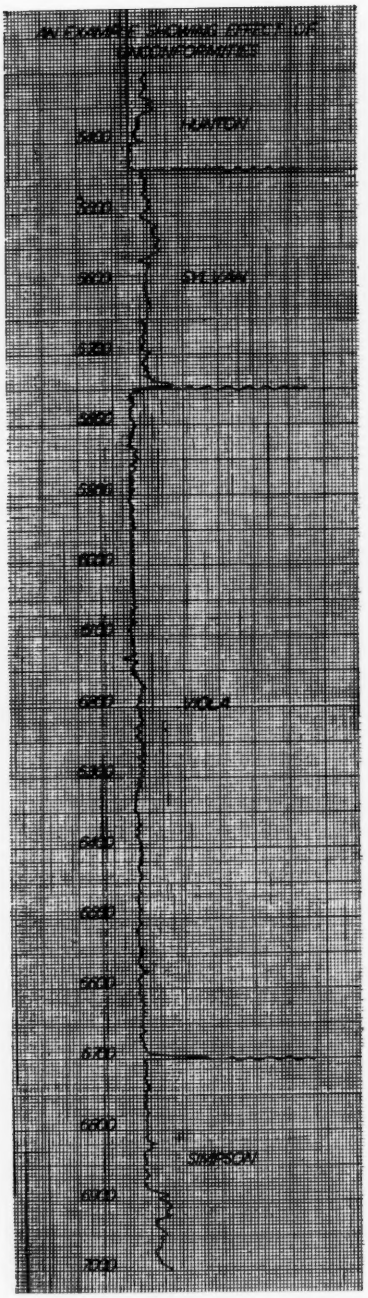
AN EXAMPLE SHOWING EFFECT OF UNCONFORMITIES
HUNTON
SYLVAN
VIOLA
SIMPSON

FIG 3

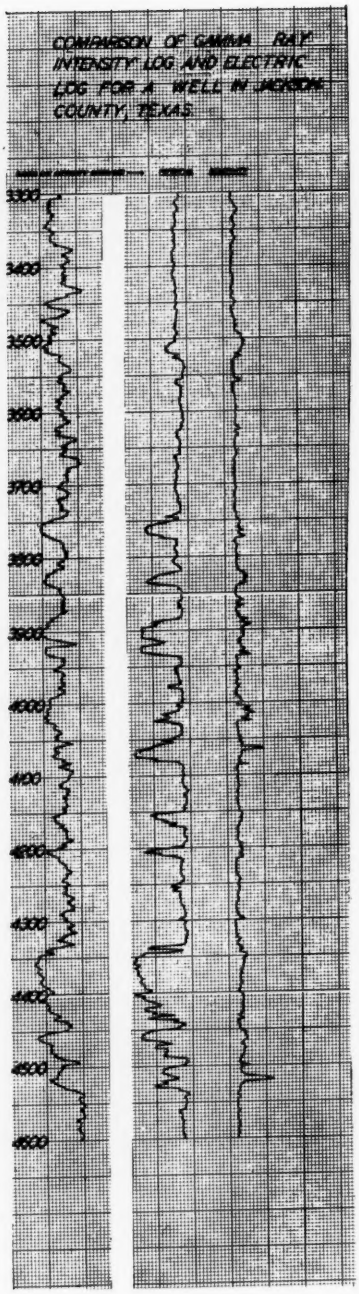
COMPARISON OF GAMMA RAY INTENSITY LOG AND ELECTRIC LOG FOR A WELL IN JACKSON COUNTY, TEXAS

FIG. 4

usually represents a period of emergence, accompanied by erosion, followed by submergence and subsequent sedimentation. During the beginning of the submergence, the deposition very likely took place in shallow waters, where much organic matter existed, which very likely concentrated the radioactive materials to some degree.

Fig. 3 also illustrates the occurrence of maxima of radioactivity in the immediate neighborhood of known unconformities. Such an occurrence can reasonably be expected if the bottom portion of the sediments deposited immediately after the period of emergence is shaly. The Fig. 3 illustrates this point quite well. The boundaries between the Viola and the Simpson Dense show a maximum, as does the boundary between the Viola and the Sylvan Shale. The unconformity at the top of the Sylvan Shale, however, does not show a maximum. This is a thing to be expected when we consider that the cleanest, most uniform part of the Hunton limestone is superimposed directly upon the top of the eroded surface. Faults, especially if they represent brecciated zones, offer more opportunity for the dissemination of fluids than do the unbroken layers. It is reasonable to expect that leaching or deposition could produce an anomaly in the gamma ray intensity curve. As yet no specific instances of this have been observed; but the evidence is extremely scanty.

Fig. 4 illustrates the ability of gamma ray measurements to be correlated with an electrical log in the same well. The illustration is of a well in the West Ranch pool northeast of Port Lavaca, Texas. It is to be noted not only that there is quite a degree of resemblance between the radioactivity log and the electrical curves, but that there are considerable differences, also. This is particularly true in the shaly section above 3,700 feet in the given example. Such differences are to be expected, because of the entirely different nature of the measurements. It is, nevertheless, not unreasonable to hope that the gamma ray curves themselves will be easily correlatable in nearby wells, throughout the strata in which the electrical logs are quite uninformative. In a recent paper of G. H. Westby and S. A. Scherbatskoy,[1] correlations are presented which illustrate this point very well.

TECHNIQUE OF RADIOACTIVITY LOGGING

For those to whom the idea of radioactivity logging is still a little

[1] G. W. Westby and S. A. Scherbatskoy, "Well Logging by Radioactivity," Oil & Gas Journal, February 22, 1940.

unfamiliar, we present a brief resume of the technique of the process, and the course of its development in our organization.

Several years ago, we undertook a systematic study of the available methods of well logging, for the purpose of selecting something new and useful for immediate development. Because it appeared to have outstanding merit, the radioactivity method was selected. Following earlier proposals of members of the staff, natural gamma radia-

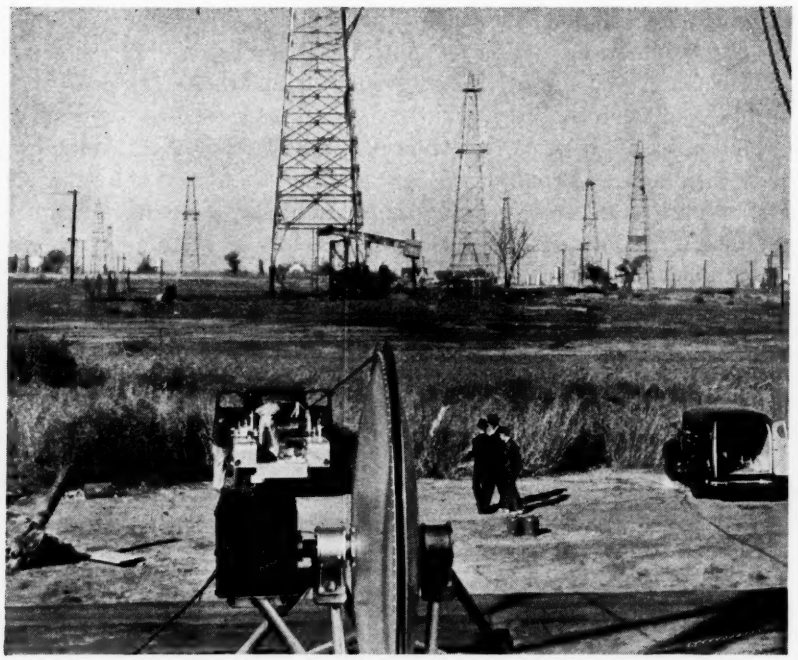

FIG. 5

tion was taken as the basis of the measurement. An instrument was very soon produced by means of which preliminary measurements were made in some cased wells, to test the possibilities of the method. These earlier measurements were made point by point, and an ionization chamber containing nitrogen under pressure was used to measure the gamma radiation. Because the ionization currents were very weak, it was necessary to design a special direct current amplifier before continuous recording could be attempted. In the fall of last year, experimental runs were undertaken on a large scale, with the newly

developed equipment. The sensitivity and precision of the new equipment is so great that one hundredth of a microgram of radium in contact with the outside of the instrument will produce a measurable deflection. This sensitivity is entirely adequate to produce significant curves, even where the variations in natural radioactivity of the rocks are quite small. By special design features, the tendency of the base line to drift has been made extremely small.

The technique of the field operations resembles somewhat the methods used for other forms of well logging. Significant improvements have been achieved in depth measuring technique by the use of a very large measuring wheel (circumference 10 feet) and a selsyn transmission system to drive the paper, and to register depth on indicating meters at the well, and in the winch truck and in the panel recording truck. An automatic pen-recorder makes the recording process visible during the entire run, enabling an immediate check on any horizon which, for any reason, shows unusual characteristics. Telephonic communication is provided to make it easy for the observer to give his orders to the winchman, or to anyone at the well. Fig. 5 shows the set-up for electrical logging under operating conditions.

It must be borne in mind that well logging, by studying the levels of radioactivity in the rocks, is very new. At this stage, it is impossible to enumerate all of the things that can be determined by analysis of the curve of the radioactivity in a bore hole. From the many logs of drilled holes already made, it is possible to deduce certain things. However, since the study of these logs, is empirical, it is quite likely that as time goes on and more and more logs are analyzed in comparison with the corresponding geologic logs, additional techniques for identifying and determining the constituency of the various rocks will be developed.

SOME NEGLECTED ASPECTS OF CHEMICAL EXPLORATION*

R. THOMAS SANDERSON†

ABSTRACT

In a general discussion of geochemical exploration for petroleum, some of the problems particularly related to the soil-analysis method are considered in detail. It is suggested that with technique now available for gas-analysis, the older method of soil-gas sampling may avoid some of the difficulties inherent in the soil-sampling method.

Recently much attention has been focused on geochemical prospecting for petroleum, and it is encouraging to note that the most recent attention has been increasingly critical. Encouraging, because the new skepticism may signify an increasing willingness on the part of the petroleum industry to devote to the problems of geochemical prospecting the careful and patient attention which they need.

In the process of development of soil analysis, much experimental work has been done, but unfortunately much of this work has apparently been in the interests of hasty commercial application rather than of sound and scientific fundamentals. It is often true that the scientific investigation of a new process is postponed until difficulties encountered in its empirical application necessitate a more thorough study. If such difficulties are never encountered, the expense of exhaustive research has thus been saved.

It is not always safe, however, to place too much confidence in any new method whose selection may have been somewhat arbitrary, because there is always a chance that in the natural eagerness to practice such a method commercially, potentially superior methods may not have received adequate attention. In this paper, the thought is advanced that perhaps soil analysis may be so classified—directed toward the desired end, but not the most desirable means. That investigations of chemical survey methods are being expanded is evidence enough that difficulties in soil analysis exist. Indeed, we shall soon see that whereas we may be surprised at the very existence of difficulties, we should have been much more surprised if soil analysis had proven completely successful. For the potential causes of failure

* Presented at the Annual Meeting, Chicago, April 9, 1940.

† Western Geophysical Company of California.

are many, and an examination of them should shed a needed light on the problems involved.

It will be well to have clearly in mind what the soil analysis method is, and what it undertakes. The fundamental assumption is by this time quite well known—that hydrocarbons from subterranean petroleum slowly leak to the surface. Soil analysis is a means of measuring those hydrocarbons at the surface, in order to locate their source. A fact vital to the utility of this or any method, which is sometimes underemphasized, is this: the analysis of soil, or any other means of chemical prospecting, is only of value insofar as, directly or indirectly, it measures the concentration of leaking hydrocarbons. Analysis of the soil is only a start. Unless soil analysis data tell the relative concentration of leaking hydrocarbons, most of their significance is lost. Let us understand throughout this discussion, that we are dealing with the problem, not merely of analyzing the soil, but of measuring leaking hydrocarbons. The method of soil analysis will stand or fall accordingly as it succeeds or fails in this measurement.

Because it is generally agreed that gaseous paraffin hydrocarbons are most direct indicators of their supposedly unique source in petroleum, let us confine our considerations to their presence and significance in surface soils.

When a gas is said to be "in a soil," what is usually meant is that the gas is sorbed by the soil. That is, the gas referred to is not the soil air which shares with water all of the space between particles of soil, but it is gas whose molecules are actually held in contact with the solid matter. In order to understand the problems involved in the soil analysis method, it is essential to have some conception of sorption phenomena. I shall endeavor first, therefore, to give as briefly as possible a simplified non-technical picture of the system, gaseous hydrocarbons in soil.

In general, each molecule of any solid substance exerts attractive forces in all directions. When a molecule is on the interior of a solid, its attractive forces are well neutralized by the other molecules which surround it. When the molecule is at the edge or surface of the solid, however, its forces are not completely occupied by other molecules of the solid, and as a result, there are free attractive forces directed out into space. It is these free forces, acting from the surface, which can hold, or sorb, gas molecules to the surface. One of the chief characteristics of soil is that it is composed of multitudes of fine particles, so that it has a total solid surface thousands of times greater than if

the same mass of soil were in a single solid bulk. Therefore, the soil has unusual ability to sorb gases.

The ability of the soil to sorb any gas will depend on three general factors, first, the kind of gas, second, the characteristics of the soil, and third, the conditions under which the soil is exposed to that gas. The first factor needs no explanation except to state the fact that all else being equal, different gases are sorbed in different amounts.

The second factor, the characteristics of the soil, is more complicated. Since sorption takes place on the surface, it is evident that in general, the more surface, the more sorption. The amount of surface, however, is not the only important characteristic of soil. Sorption will also depend on the type of surface, its physical shape and chemical composition. Since the surface will under natural conditions be considerably modified by the presence of previously sorbed molecules such as carbon dioxide, water, and air, as well as mineral ions, this sorbed layer of impurities should perhaps also be considered partly as a characteristic of the soil.

The third factor, conditions of sorption, is equally complicated and equally important. Sorption will depend on the temperature, on the pressure of the particular gas considered, and on the length of time of exposure. Since the gas must compete for positions on the soil surface with other gas molecules with which it may be mixed, the amount of sorption will also be dependent on the concentration and kind of other gases present in the mixture.

The difficulties in soil analysis begin in attempting, first to measure, then to interpret, the results of so complicated a situation. No two samples of soil are identical. Therefore for each sample of soil, as well as for each possible set of conditions, there is a single separate, correct interpretation of the analytical results. Any general interpretations, in which the data have collectively been subjected to a standard treatment, are at best only approximations. The practical question is, can they be good approximations?

There is no absolute answer to that question, but some conception of the difficulties inherent in interpreting the actual soil analysis data can be gained from considering the problems in greater detail. To do this, let us take a typical sample of soil and study it with reference to these problems.

Assumining that sampling can be accomplished without complications, the first job is to analyze this sample for gaseous hydrocarbons. All known methods of analysis require initially the separation of the

hydrocarbons from the soil. Let us use any means of separation, then, in which the hydrocarbons are not altered or destroyed or lost. How shall we know when, or if, the separation is complete? That this is not easy can be demonstrated.

We have a sample of soil of unknown composition, from which we have separated a very small amount of hydrocarbons. The only absolutely positive means of determining whether any hydrocarbons are left in the soil would be to subject the soil to a complete and exceedingly accurate quantitative analysis, because any unknown residual component may contain hydrocarbons unless its composition is otherwise established. Any chemist will agree that such an analysis would be a practical impossibility.

Thus we must depend on lesser means for any assurance of complete separation. For example, if we repeat the separation procedure on the same soil sample, and get no additional hydrocarbons, it may seem reasonable to suppose the original treatment to have been adequate. Unfortunately, however, individual molecules in different positions are sorbed with differing amounts of force, and therefore are not separable with the same ease. There is no way to be positive that the chosen method is sufficiently vigorous to effect a quantitative separation, regardless of how long the method may be applied.[1]

Further, the method cannot be adequately tested by laboratory experiments with synthetic atmospheres, because it is impossible to reproduce unknown natural conditions, or the known conditions of long time exposure of the soil to traces of hydrocarbons. There is no reason to believe that the characteristics of long time sorption under variable conditions can be understood from controlled studies of sorption over very short periods of time. Admitting the possibility that the separation by some method may be complete, yet the characteristics of sorption are such that there is no practical way to learn positively whether that is actually the case.

On the other hand, perhaps there is no need for complete separation. If we know that our method separates approximately the same

[1] In this connection, it is interesting to consider the experience in determining gases in rocks described by E. S. Shepherd in "Gases in Rocks and Some Related Problems," published in Amer. J. Science, 35A, 311 (1938). Mr. Shepherd says that if the temperature is raised above that used in initially outgassing rocks, more gas will be given off. "In fact," he writes, "there is no practical limit to this evolution. Only by adopting a definite procedure can one hope to duplicate one's results."

It has been our experience in soil analysis that higher temperatures invariably produce larger amounts of desorbed gas.

proportion of the total sorbed hydrocarbons from all soils, we do not really care whether or not the separation is quantitative. But if the completeness of separation is open to doubt, there is even greater reason for doubting that the same proportion will be desorbed from different soils by the same treatment. Indeed, on the basis of analogous chemical experience, we should conclude quite the opposite. It is most likely that the same process would separate different proportions from different soils.[2] Thus we see that separating the sorbed gases from the

[2] A clearer idea of the differences in soils can be gained from examining some of the data obtained in an investigation of methods of determining moisture in soils, which was conducted by D. S. Rearden in the Geochemical Laboratory of the Western Geophysical Company. For water which is not chemically bound, it might be expected that heating in a well-ventilated oven at 110°C for an hour should dry soil fairly effectively. Notice, however, the results of such treatment, which was identical for each soil sample:

Soil Type (By Inspection)	*Oven Drying* % *of Total* H_2O *lost after: (Hours)*									*Total Drying Time*
	%H_2O*	0.5	1	2	3	4	5	6	7	8	
Adobe	25.9	42.5	68.8	89.6	99.3	100					4
Adobe	4.6		32.0	56.5	80.5	87.0	91.5	98.0	100		7
Clay	4.4	27.0	46.0		79.7	86.6	93.2	95.5	98	100	8
Sandy Clay	3.4	34.0		64.6	69.6	82.5	88.4	91.3	97.0	100	8
Sandy Clay	9.2	68.5	99.0	99.0		99.0		100			6
Loam	11.6	82.7	100								1
Sandy Loam	3.7	70.3	78.5	97.4		97.4		100			6
Sandy Loam	1.6		95.6	98.8	99.4	100					4
Sandy Loam	1.1	91.0	100								1
Wet Sand	29.2	56.8	93.0	99.0	99.5	99.5	100				5
Beach Sand	0.19	58.0	89.5	89.5		89.5		94.5		100	8

(* As determined by heating at 110°C. to constant weight. It is interesting to note further that according to Meyer and Anderson, in "Plant Physiology" the amount of water driven off by heating, even well above 110°C., is a function of the temperature.)

Some of these same samples of wet soil were evacuated at room temperature, with the following results:

Soil Type	%H_2O	*Evacuation* % *Total* H_2O *lost after: (Hours)*				
	(By Oven)	0.25	0.50	0.75	1.00	1.25
Adobe	25.9	1.43	32.6	51.0	65.0	74.0
Clay	4.4	6.3	24.8	44.5	49.5	
Sandy Clay	9.2	44.5	58.8	67.3	75.0	
Loam	11.6	38.9	57.7	73.2	79.2	
Sandy Loam	1.6	12.3	17.3	21.0	41.0	
Sandy Loam	1.1	20.9	26.4	30.0	31.8	32.6
Wet Sand	29.2	18.1	23.3	28.4	30.4	

Notice that the relative rates of drying by evacuation and by heating are not equal; for example, adobe containing 25.9% H_2O loses 68.8% of it on heating for one hour and 65.0% of it on evacuation for one hour, whereas sand containing 29.2% H_2O loses 93% of it on heating for one hour, but only 30.4% of it on an hour's evacuation.

soil may itself be a problem much more difficult than commonly appreciated.

After having successfully separated the hydrocarbons, we should be able to leave the problem of purification and measurement to the capable chemist. So much then, for the separation and analysis. We should not view this problem of chemical technique with undue pessimism, for maybe it is not serious. Remembering, however, that there is a maybe, let us now assume that we have accurately determined the concentration of hydrocarbons contained in our soil sample. If we have accomplished the analysis of the soil, we should remember that it is only the beginning.

The next problem is, what does the analytical result represent, or, what does it signify? In order for us to correlate the soil analysis data with the absence or presence of subterranean petroleum, the analytical result must in some way be a measure of the concentration of hydrocarbons rising from the depths. In other words, the concentration of hydrocarbons in the soil is a measure of the concentration in the environment of that soil, namely, in the soil air. In order to learn about petroleum beneath, we must know how to interpret our soil analysis data in terms of the hydrocarbon concentration of the soil air.

Here we come to a specific example of the general sorption problem previously described. A solid, our soil sample, which has been exposed to a gas, soil air, contains a concentration of hydrocarbons which we have measured. What has been the concentration of hydrocarbons in the soil air?

It is clear that we are too ignorant of conditions of sorption and other factors to be able to calculate this value absolutely. This inability need not concern us, however, if the relation between soil and soil-gas hydrocarbon concentrations remains approximately constant throughout the region being surveyed. Only relative hydrocarbon values over an area are of particular interest in geochemical prospecting. This means that our soil analysis result must equal that from any other soil sample exposed to the same concentration of hydrocarbons, or conversely, equal results from different soils must signify the same soil gas concentration.

Remembering what was said earlier about sorption, this could only

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It is by no means intended to imply that sorption of water by soils is closely comparable to their sorption of gaseous hydrocarbons. Nevertheless, these data are clearly illustrative of the soil differences which complicate the analytical problem.

be true if both the conditions of sorption and the types of soil were identical. Concerning the conditions of sorption, the number of possible independent variables is so great as to make it highly improbable that they would be the same at separate places. As for soils, it is well known, of course, that wide variations exist and may occur within a very small area. Any soil difference is likely to be reflected in a difference in ability to sorb. From direct measurement in our own laboratory we know that dry soils may differ by a factor as great as six in their ability to sorb hydrocarbons.[3] Although these tests were not made under naturally occurring conditions, they clearly demonstrate the variation among soils. Since both soil type and sorption conditions are variable from place to place, it seems essential, in order to interpret or compare soil analysis data intelligently, to apply some means of correction.

These important variables, soil type and sorption conditions, must be closely related in the correction problem, because the soil type is only important for its effect on the sorptive ability, and the sorptive ability in turn is dependent on the sorption conditions. In order to attack this correction problem, however, it seems better to consider these two phases of it separately, while remembering their close interrelationship.

Let us consider first how to evaluate differences in soil types as indicated by their different sorptive abilities. Could the difference in sorptive ability be reliably corrected for? Perhaps it would seem simple to do this, just by measuring relative sorptive capacities and correcting the analytical data accordingly. Unfortunately, the problem seems far more complicated than that. As has been previously stated, the

[3] The sorption of natural gas, and of air, each at one atmosphere pressure, by four different types of soils was studied in the Geochemical Labratory of the Western Geophysical Company by E. G. Brewster, some of whose data are here tabulated:

Soil Type	*% H_2O (of Water Sample)*	*Sorption (in cc. per Gram)*		
		Wet	*Dry*	*Evacuated 2.5 Hours at 110°C.*
Adobe	4.5	0.05 nat. gas 0.06 air	0.45 nat. gas 0.16 air	0.60 nat. gas 0.25 air 0.19 oxygen
Clay	4.6	0.06 nat. gas 0.05 air	0.28 nat. gas 0.10 air	
Sandy Clay	9.3	0.03 nat. gas 0.05 air	0.16 nat. gas 0.06 air	
Loam	11.7		0.07 nat. gas 0.07 air 0.07 oxygen	0.11 nat. gas 0.06 air 0.07 oxygen

capacity of a soil to sorb hydrocarbons is dependent not only on the characteristics of the soil, but also on the conditions of sorption. It is by no means certain that the relative sorption of two soils will be the same for example, under a sorption pressure of one millionth of an atmosphere as it is under one atmosphere. In experiments which have involved exposure of a solid to a gas for a long period of time, there has been a fairly rapid sorption of a rather definite amount of gas, and then the solid has commonly been found to continue to sorb the gas very slowly but for an indefinitely long period. Thus, the probable long exposure of soil in the ground to small concentrations of hydrocarbons has had an important effect. All portions of the soil surface are not equally accessible to gas molecules, and therefore there might be a great difference between the total sorptive capacity and the amount of superficial sorption which could take place during a relatively brief exposure period.[4]

It is conceivable that the whole picture may be additionally complicated by the fact that, like all colloidal systems subject to varying conditions, the very character of the soil is constantly, though slowly, changing, and therefore the potential sorptive capacity of any particular soil is probably not constant over a considerable period of time.

At any rate, we have seen that to obtain a reliable correction factor for soil differences would be a difficult problem indeed.

Now, for the sake of discussing the second phase of the correction problem, suppose the soils were exactly alike in sorptive ability. Or, let us suppose that we have succeeded in developing an approximately valid correction for soil differences. What, if anything, do we know about the conditions of sorption? Remember that the conditions are every bit as important as the nature of the soil itself.

For example, during the period of sorption, what was the water content of the soil? Did it vary? Was it the same for each sample? Do we have any reason for believing that in a long period of time the effect of water on hydrocarbon sorption can be neglected? In our laboratory we have measured the sorptive capacity for hydrocarbons

[4] Some qualitative indication of this is seen in the following data obtained in the hydrocarbon sorption studies by Brewster.

Type of Soil	*Sorption (cc of Hydrocarbon\gm) at Apparent Equilibrium—Reached in 10 Minutes*	*Sorption after Longer Time*	
		Hours	*Sorption*
Adobe	0.43	15	0.50
Clay	0.24	63	0.33
Sandy Clay	0.14	15	0.22

of naturally wet soils and found it, during several hours, to be only a small fraction of the dry sorptive capacity of these same soils. (See Footnote 3.) Further, we have found in the field, places where samples from the same depth only twenty feet apart horizontally on level ground, differed from each other in water content by as much as fifteen per cent of the total soil weight. Evidently there is real need for investigation here if soil analysis data are to be worthy of confidence.

Now, let us consider the possible effect of other gases on the sorption of hydrocarbons. Suppose there are present, as there may be, an appreciable number of molecules of such a readily sorbed gas as, for example, carbon dioxide. Is the effect of carbon dioxide on hydrocarbon sorption known? Is it the same for all soils? It is a general observation that more-readily sorbed gases can displace less-readily sorbed gases from a solid surface. Can carbon dioxide displace butane, for example? It is also known that the carbon dioxide content of soil air differs from place to place. Thus, another doubt casts its shadow on soil analysis.

Now let us pause to summarize these difficulties encountered in the soil analysis method. We have seen that in the first place, it is not possible to be certain of the accuracy of the analytical results. In the second place, if we do succeed in obtaining acceptable analytical data, we still face the much more difficult problem of interpreting them in terms of concentrations of hydrocarbons leaking from petroleum reservoirs. This problem is made difficult by the differences in soils and by the differences in conditions of sorption. We have seen that at best only a roughly approximate measurement of significant soil differences can be made. Finally, even if the soil differences are successfully evaluated, we encounter the practically insurmountable obstacle of being completely ignorant of the conditions under which the soil was exposed to hydrocarbon gases.

From thorough consideration of these problems, one would probably conclude that soil analysis can hardly be a successful method of prospecting for oil unless its data can be subjected to a variety of complicated correction factors capable of making the data approximately comparable.

If the actual application of the soil analysis method were generally successful, it would be fair to assume either, that complications such as mentioned in this paper are not serious, or, that adequate corrections are being applied. However, the method has not been proven. While it is not fair to condemn the method for sometimes failing,

neither does it seem completely fair to credit it with success where it was not only supplemented by other geophysical data, but where in fact these data may have been of invaluable assistance in the interpretation of the geochemical data. As for interpretation theory, that currently advanced is based on observations of data which, as we have noted, may have been in error, and in all probability did not correctly represent the actual relative concentrations of leaking hydrocarbons. In my opinion, therefore, there is nothing unexpected in the failure of soil analysis data to establish such theory convincingly, or in the failure of such theory to provide a reliable basis for locating petroleum.

It would seem that the future development of the soil analysis method should be directed toward the solution of such problems as presented here, and very possibly it is being so directed now. It also would seem that the solution of these problems may be extremely difficult. The prospect of evolving adequate means of correction thoroughly founded on sound theoretical considerations is dimmed by the realization of the extremely complicated nature of the task. It seems more likely that a practical solution will be dependent on the chance accuracy of empirical correction methods. If these are used, they cannot be relied upon to increase the accuracy, except as their reliability may be established by thousands of actual tests. Such tests are and will be expensive, as any trial and error method may be.

I have intended to imply no conviction that such methods are impossible. Indeed, it has been difficult in presenting fairly the facts of this paper, to avoid creating unintentionally a feeling of pessimism such as is justly unwelcome in so new a field. If the problems of soil analysis seem discouraging, then, it is only because they are, in themselves, obviously difficult. As a matter of fact, as long as the fundamental premise of hydrocarbons leaking from a unique source, petroleum, is not disproven, the hope of some degree of success is alive and encouraging, whatever the difficulties may be. The very simplicity of the premise, however, makes the complexity of the method seem incongruous and it is not without good reason that we begin to wonder if soil analysis is really the answer.

From a study of the situation, the thought occurs that perhaps we are making too much work of this problem. Instead of struggling with soil analysis, which after all is intended as a means of revealing the hydrocarbon concentration of the soil air, why not analyze the soil air?

This was apparently the first method of geochemical prospecting,

and no conclusive evidence about it has been published. Apparently the soil-gas method has never been thoroughly tested. The substitution of soil analysis seems to me to have been a very unfortunate development in chemical surveying, because it was the displacement of an inadequately tested direct method by an unproven indirect method. If the data from soil-gas analysis cannot be interpreted in terms of the presence or extent of subterranean petroleum, soil analysis, so dependent on soil-gas hydrocarbons, could hardly be expected to be worth while.

It is probably true that the early difficulties experienced in efforts to obtain accurate, representative samples of soil gas, did much to encourage the abandonment of the soil gas method in favor of soil analysis. Soil sampling appeared to be much easier and more accurate. Recent developments, however, have altered this situation notably. New techniques of soil-gas sampling have been developed by which the soil gas may be accurately and conveniently sampled practically any where the soil may be sampled. The theoretical advantages of soil-gas analysis over soil analysis are clearly demonstrated by the discussion of soil analysis problems in this paper. There are no differences in air the world over to correspond to differences in soils. The concentration of hydrocarbons in air may be considered independent of the other composition of the air. Soil gas containing, for example, one part per million of gaseous hydrocarbons is for practical purposes the same, no matter where it may be taken. The analysis of soil gas is equally straightforward. There is no question about the separability of the gaseous hydrocarbons from air; if the method of measurement requires it, it is easily and quantitatively done.

It should hardly be necessary to say that the gas-analysis method is not a "cure-all." There are problems confronting it, of course. But, since it avoids so many of the uncertainties which cast doubt on soil analysis, let's try it. In practice, the new development of this old method is still young, but as the gas method is developed and given an opportunity to prove its worth, its data may be found to be a more reliable indication of hidden oil. It is hoped that the results of present investigations in this field will be available for publication in the near future.

The appreciation and thanks of the author are here expressed to Mr. Henry Salvatori, whose stimulating discussions have been very helpful, and to Mr. E. G. Brewster and Mr. D. S. Rearden, whose careful work and critical thought have contributed much to the formulation of ideas herein presented.

FORMULAS AND CURVES FOR THE INTERPRETATION OF CERTAIN TWO-DIMENSIONAL MAGNETIC AND GRAVITATIONAL ANOMALIES*

HAROLD H. PENTZ†

ABSTRACT

Curves and formulas for the interpretation of the two-dimensional "dike" and "step" are given because they offer an easy, rapid method of solving all cases to which they apply. Horizontal and vertical polarization of the bodies are considered. This method applies to torsion balance surveys, and to magnetic surveys where the horizontal and vertical components of the earth's magnetic field are measured. Two curves for the interpretation of an anomaly in terms of a point pole (or a point mass) are given. The depth to the two-dimensional structures is considered, with formulas and curves.

INTRODUCTION

Formulas and curves for the interpretation of magnetic and gravitational anomalies in terms of geologic structure have been given by previous publications. Heiland[1] has summarized the current rules used in estimating the depth to magnetic anomalies. Smyth[2] gives formulas for the attraction of magnetic bodies while Shaw[3] gives formulas and curves for the interpretation of gravitational anomalies. The method of Nippoldt[4] requires no assumption as to the causes of magnetization of the subsurface region. Eötvös first pointed out the fact that the formulas and curves, which are used for the interpretation of magnetic surveys, apply directly to gravitational surveys made with the Eötvös torsion balance. These methods of interpretation include some cases where the observed magnetic anomalies are due to increased magnetism and others in which there are permanently magnetized zones in the subsurface of the earth. The methods given in the present paper will be discussed primarily for magnetometric surveys, but they apply equally well to torsion balance surveys.

Discussion will be limited to two-dimensional problems, that is,

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† Bethlehem, Pa.

[1] C. A. Heiland, Discussion, Trans. A. I. M. E. 97, 212–214 (1932).

[2] H. L. Smyth, "Magnetic Observations in Geological Mapping," Trans. A. I. M. E. 26, 640–709 (1896).

[3] H. Shaw, "Interpretation of Gravitational Anomalies, I and II," Trans. A. I. M. E. 97, 271–366 (1932).

[4] A. Nippoldt, Verwertung magnetischer Messungen zur Mutung, Berlin 1930.

to geologic structures which are so long in one horizontal direction that the length may be considered infinite. These structures may be represented by slabs of one material, having uniform properties throughout, which are imbedded in a uniform material having different properties. If the slab is vertical, as shown by Fig. 1, the structure

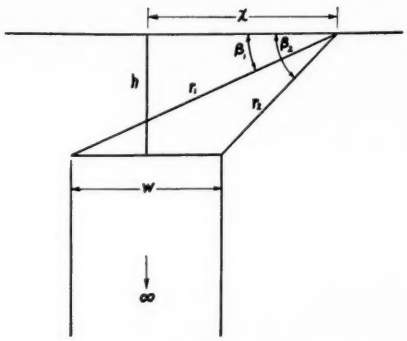

FIG. 1. Vertical projection of a two-dimensional "dike."

will be called a "dike"; if it is horizontal, as in Fig. 2, the structure will be called a "step." The curves given are independent of the value

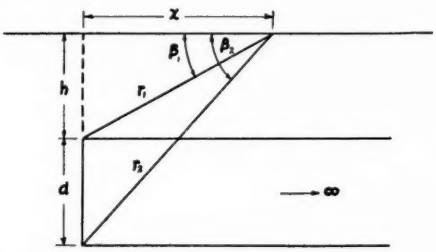

FIG. 2. Vertical projection of a two-dimensional "step."

of the intensity of magnetization and of the system or units of measurement. They are dependent on the depth to the structure and the thickness of the step or the width of the dike. Similar structures will give the same curves, i.e., if the width (or thickness) and the depth of one structure are each multiplied by the same constant a similar structure will be produced. These structures may be magnetized horizontally or vertically. In the gravitational case, these curves and formulas apply directly as the strike of the body may lie in any direc-

tion. Tables 1 and 2 list in conventional form the formulas for the two dimensional structures that are treated here.

Curves for the interpretation of anomalies in terms of a single magnetic pole are also included.

TABLE 1

Formulas for a dike. (*See Fig. 1.*)

$\Delta H = 2m \log_e \frac{r_1}{r_2}$	Vertical polarization
$\Delta Z = 2m(\beta_2 - \beta_1)$	
$\Delta H = 2m(\beta_2 - \beta_1)$	Horizontal polarization
$\Delta Z = 2m \log_e \frac{r_1}{r_2}$	
Gradient $= 2G\rho \log_e \frac{r_1}{r_2}$	Gravity
Curvature $= -2G\rho(\beta_2 - \beta_1)$	

TABLE 2

Formulas for a step. (*See Fig. 2.*)

$\Delta H = -2m \log_e \frac{r_2}{r_1}$	Vertical polarization
$\Delta Z = 2m(\beta_2 - \beta_1)$	
$\Delta H = 2m(\beta_2 - \beta_1)$	Horizontal polarization
$\Delta Z = 2m \log_e \frac{r_2}{r_1}$	
Gradient $= 2G\rho \log_e \frac{r_2}{r_1}$	Gravity
Curvature $= -2G\rho(\beta_2 - \beta_1)$	

G=universal gravitational constant; m=intensity of magnetization; ρ=density.

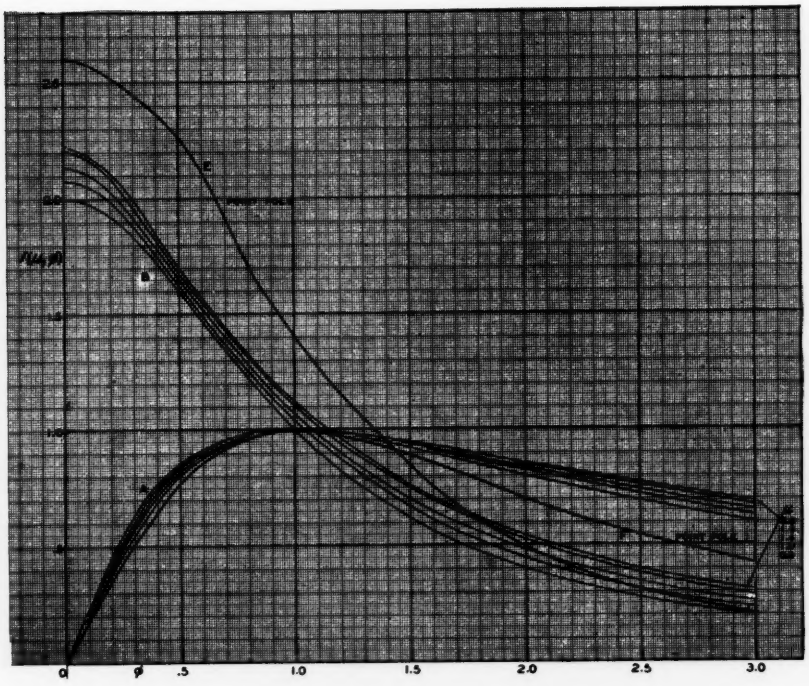

FIG. 3. Type curves used in the interpretation of a "dike" and a point pole.

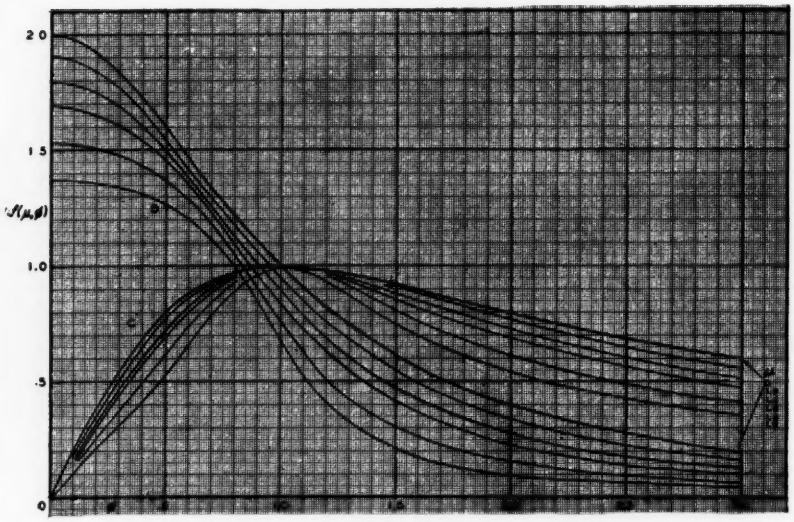

FIG. 4. Type curves used in the interpretation of a "step."

The formulas and curves here published are given because they offer an easy, rapid method for solving all problems to which they apply.

DERIVATION OF FORMULAS

For the purpose of continuity, two complete derivations will be given; one for the dike with vertical polarization (north or positive poles are on the top of the dike), and the other for the step with horizontal polarization (north poles are along the face of the step).

The derivation may be made in several steps. The magnetic field due to an infinite horizontal line of north poles is derived as follows:

1. From a pole of strength m there are $4\pi m$ lines of force.

2. For a line of poles, m poles per centimeter length, by symmetry the lines of force are at right angles to the line.

3. Draw (Fig. 5) a cylinder of radius r, one centimeter long, the center line coinciding with the line of poles; then

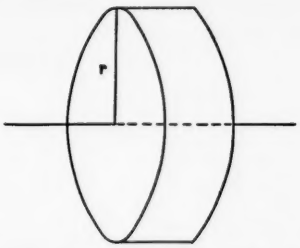

FIG. 5. Magnetic field produced by a one centimeter length of an infinite line of poles.

m = total number of poles included,
$4\pi m$ = total number of lines of force originating in the cylinder,
$2\pi r$ = total surface through which they come out,
$2m/r$ = field strength or number of lines per square centimeter.

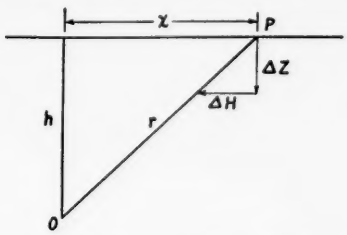

FIG. 6. Component of the magnetic field at a point P, produced by an infinite line of poles whose trace is O.

Let the point O in Fig. 6 be the trace of the line of poles. Then the field at P is:

$$H_P = 2m/(x^2 + h^2)^{1/2}. \tag{1}$$

The horizontal component of the field at P is:

$$\Delta H = 2mx/(h^2 + x^2). \tag{2}$$

The vertical component of the field at P is:

$$\Delta Z = 2mh/(h^2 + x^2). \tag{3}$$

1. DIKE—VERTICAL POLARIZATION

Referring to Fig. 7, and using equations 2 and 3 for the elementary components due to an infinite line of north poles along the top of the

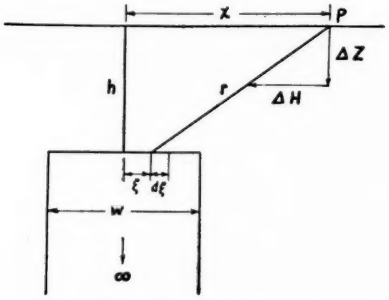

FIG. 7. Components of the magnetic field produced by an infinite line of north poles along the top of the "dike."

dike, the horizontal and vertical components of the magnetic field at a point P are:*

$$\Delta H = \int_{-w/2}^{+w/2} \frac{2m(x - \xi)d\xi}{h^2 + (x - \xi)^2} = m \log_e \frac{h^2 + \left(x + \frac{w}{2}\right)^2}{h^2 + \left(x - \frac{w}{2}\right)^2}$$

$$= m \log_e \frac{1 + \phi^2 + \mu\phi}{1 + \phi^2 - \mu\phi}. \tag{4}$$

$$\Delta Z = \int_{-w/2}^{+w/2} \frac{2mh\, d\xi}{h^2 + (x - \xi)^2} = 2m \tan^{-1} \frac{wh}{h^2 + x^2 - \frac{w^2}{4}}$$

* Note that m is now the intensity of magnetization.

$$= 2m \tan^{-1} \frac{\mu\left(1 - \frac{\mu^2}{4}\right)^{1/2}}{1 + \phi^2 - \frac{\mu^2}{2}}. \tag{5}$$

where the abscissas for the extreme values of ΔH are $X = \pm(h^2 + w^2/4)^{1/2}$, $w = \mu X$, $x = \phi X$, and $h = X(1 - \mu^2/4)^{1/2}$.

Substituting $\phi = 1$ in equation 4 to obtain the maximum of ΔH and dividing equations 4 and 5 by this maximum, the equations, graphically represented in Fig. 3, are:

$$A(\mu, \phi) = \frac{\Delta H}{\Delta H_M} = \log_e \frac{1 + \phi^2 + \mu\phi}{1 + \phi^2 - \mu\phi} \Big/ \log_e \frac{2 + \mu}{2 - \mu}. \tag{6}$$

$$B(\mu, \phi) = \frac{\Delta Z}{\Delta H_M} = 2 \tan^{-1} \frac{\mu\left(1 - \frac{\mu^2}{4}\right)^{1/2}}{1 + \phi^2 - \frac{\mu^2}{2}} \Big/ \log_e \frac{2 + \mu}{2 - \mu}. \tag{7}$$

2. STEP—HORIZONTAL POLARIZATION

Referring to Fig. 8, and using equations 3 and 4 for the elementary components due to an infinite line of north poles along the face of the

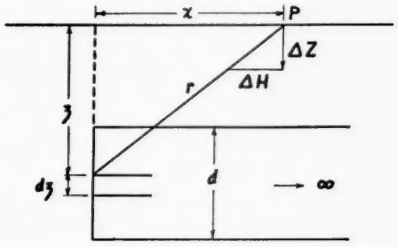

FIG. 8. Components of the magnetic field produced by an infinite line of north poles along the face of the "step."

step, the horizontal and vertical components of the magnetic field at a point P are:

$$\Delta H = \int_h^{h+d} \frac{2mxdz}{x^2 + z^2} = 2m \tan^{-1} \frac{xd}{h^2 + hd + x^2}$$
$$= 2m \tan^{-1} \frac{\mu\phi}{\phi^2 + 1}. \tag{8}$$

$$\Delta Z = \int_h^{h+d} \frac{2mzdz}{x^2+z^2} = m \log_e \frac{x^2+(h+d)^2}{x^2+h^2}$$
$$= m \log_e \frac{2(\phi^2+1)+\mu^2+\mu(\mu^2+4)^{1/2}}{2(\phi^2+1)+\mu^2-\mu(\mu^2+4)^{1/2}}. \tag{9}$$

where the abscissas for the extreme values of ΔH are $X = \pm[h(h+d)]^{1/2}$, $d=\mu X$, $x=\phi X$, and $h=[-\mu+(\mu^2+4)^{1/2}]X/2$.

Substituting $\phi=1$ in equation 8 to obtain the maximum of ΔH and dividing equations 8 and 9 by this maximum, the equations are:

$$C(\mu, \phi) = \frac{\Delta H}{\Delta H_M} = \tan^{-1}\frac{\mu\phi}{\phi^2+1} \Big/ \tan^{-1}\frac{\mu}{2}. \tag{10}$$

$$D(\mu, \phi) = \frac{\Delta Z}{\Delta H_M}$$
$$= \log_e \frac{2(\phi^2+1)+\mu^2+\mu(\mu^2+4)^{1/2}}{2(\phi^2+1)+\mu^2-\mu(\mu^2+4)^{1/2}} \Big/ 2\tan^{-1}\frac{\mu}{2}. \tag{11}$$

These formulas are plotted in Fig. 4 for different values of μ.

3. LIMITING CASE

For the limiting case, where the step or the dike becomes very thin compared to its depth, the equations 6, 7, 10, and 11 approach limiting forms which may be obtained by letting μ approach zero. Or in either the dike or step structure, when this limit is reached, the anomaly can be represented as due to an infinite line of poles (or an infinite sheet of dipoles).

Referring to Fig. 6, and using equations 2 and 3, the horizontal and vertical components of the magnetic field at a point P right or left of the infinite line of north poles are:

$$\Delta H = \frac{2mx}{x^2+h^2} = \frac{2m\phi}{X(\phi^2+1)}. \tag{12}$$

$$\Delta Z = \frac{2mh}{x^2+h^2} = \frac{2m}{X(\phi^2+1)}. \tag{13}$$

where the abscissas for the extreme values of ΔH are $X=\pm h$, and $x=\phi X$.

Substituting $\phi=1$ in equation 12 to obtain the maximum of ΔH

and dividing equations 12 and 13 by this maximum, the equations are:

$$A'(\phi) = \frac{\Delta H}{\Delta H_M} = \frac{2\phi}{\phi^2 + 1}. \tag{14}$$

$$B'(\phi) = \frac{\Delta Z}{\Delta H_M} = \frac{2}{\phi^2 + 1}. \tag{15}$$

4. POINT POLE

Referring to Fig. 9, it is easy to demonstrate that the horizontal

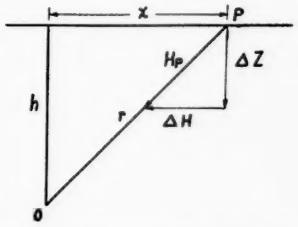

FIG. 9. Components of the magnetic field produced by a point pole.

and vertical components of the magnetic field at a point P, for a point north pole of strength m, are:

$$\Delta H = mx/r^3 = \frac{m\phi}{X^2(\phi^2 + 2)^{3/2}}. \tag{16}$$

$$\Delta Z = mh/r^3 = \frac{\sqrt{2}\, m}{X^2(\phi^2 + 2)^{3/2}}. \tag{17}$$

where the abscissas for the extreme values of ΔH are $X = \pm h/\sqrt{2}$, $x = \phi X$, and $h = \sqrt{2}X$.

Substituting $\phi = 1$ in equation 16 to obtain the maximum of ΔH and dividing equations 16 and 17 by this maximum, the equations are:

$$E(\phi) = \frac{\Delta H}{\Delta H_M} = \frac{\sqrt{27}\,\phi}{(\phi^2 + 2)^{3/2}} \qquad \left(= \frac{3\sqrt{3}\,\phi}{(\phi^2 + 2)^{3/2}}\right). \tag{18}$$

$$F(\phi) = \frac{\Delta Z}{\Delta H_M} = \frac{\sqrt{54}}{(\phi^2 + 2)^{3/2}} \qquad \left(= \frac{3\sqrt{6}}{(\phi^2 + 2)^{3/2}}\right). \tag{19}$$

These equations are plotted in Fig. 3.

METHOD OF USING CURVES

In order to use functions A, B, C, and D, the geologic structure must approximate either a dike or a step. That is, in either the magnetic survey or the gravitational survey, one curve must be like functions A and C, and the other curve must be like functions B and D. Figs. 3 and 4 are used in the interpretation. These curves are drawn for different values of μ, while ϕ remains the same for each set of curves. While the sign of these functions is positive as drawn in the first quadrant using rectangular coordinates, the sign is not necessarily positive; for example, if the formulas for the dike were developed with south poles along the top of the dike, the sign of the functions would be negative. Two methods of polarization are considered. They are horizontal polarization and vertical polarization. Although only one method of polarization is used in each derivation, the same formulas are used for the other polarization; since the formulas for the horizontal and vertical magnetic intensities will be interchanged. For example, function A will represent the horizontal magnetic anomaly if the polarization of the dike is vertical, and it will also represent the vertical magnetic anomaly if the polarization of the dike is horizontal.

The observed curves must be changed in order to use this method of interpretation. Take the curve that has two extreme values, that is, functions like A or C. Let the difference in ordinates between these two extreme values by $2Y$ and the corresponding difference in abscissas be $2X$. Then:

1. Divide each ordinate of the observed curves by Y.
2. Divide each abscissa of the observed curves by X.
3. Plot the new curves to the same scale as the curves in Figs. 3 and 4.

If the geologic structure is a dike or a step with either horizontal or vertical polarization producing the magnetic anomaly, the new curves will approximate one pair of the given curves corresponding to a definite value of μ. The width of the dike (or thickness of the step) is μX. The depth is obtained from the suitable formula in Table 3. The intensity of magnetization (m) may be obtained from equation 5 or 9. The method of interpretation is similar in the case of the point pole and the data obtained with the torsion balance.

Table 3 contains four depth rules that are included in this paper. Two of them are in conventional form and the other two are plotted. The depth rule for the dike is found in Fig. 10, while Fig. 11 contains

TABLE 3
Depth rules.

Dike	$h = X(1 - \mu^2/4)^{1/2}$	
Step	$h = [-\mu + (\mu^2 + 4)^{1/2}]X/2$	
Limiting case for dike or step	$h = X$	conventional form
Point pole	$h = \sqrt{2}\,X$	conventional form

h=depth; X=half the distance between extremes; μ=width/X for the dike and thickness/X for the step.

the depth rule for the step. In each case, the depth h is the ordinate and μX, the width or thickness, is the abscissa. As plotted, the formulas for the depth of the dike, and of the step, represent a system of straight lines intersecting at the origin, with the slope decreasing with

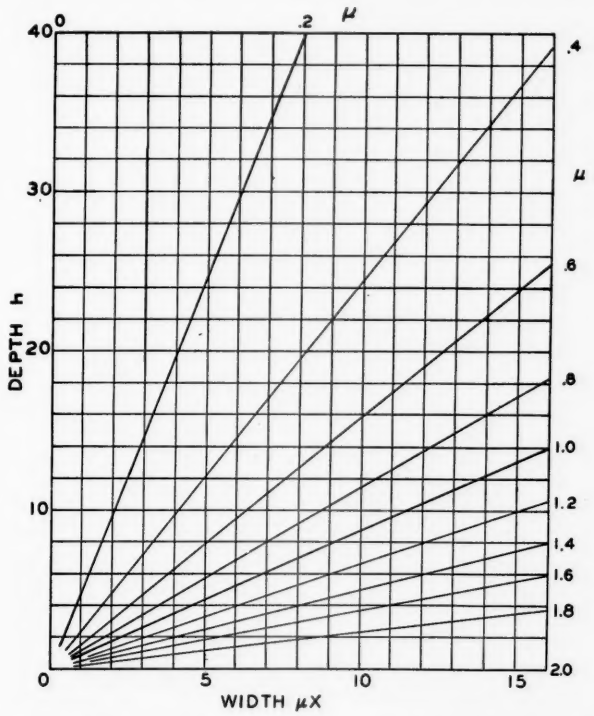

FIG. 10. Graph for determining the depth to the "dike." The dimensions of the units are dependent upon and consistent with the dimensions of X, i.e., if X is in feet, h is in feet.

increase of μ. In the dike μ varies from zero to two. In the step μ varies from zero to infinity.

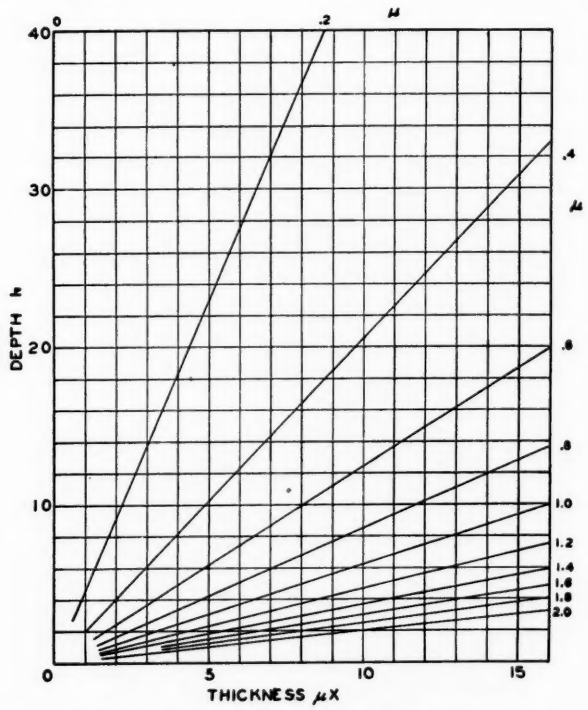

FIG. 11. Graph for determining the depth to the "step." The dimensions of the units are dependent upon, and consistent with, the dimensions of X, i.e., if X is in feet, h is in feet.

In general, magnetic measurements are not made in a line perpendicular to the strike of the anomaly, but are made in the magnetic meridian and perpendicular to it. Therefore if the strike of the anomaly is not magnetic east and west, the measurements must be multiplied by the cosine of the acute angle between it and magnetic north. The regional effect must also be removed from the survey.

ACKNOWLEDGMENT

I am indebted to Dr. Maurice Ewing whose assistance has made this paper possible.

PATENTS

ELECTRICAL PROSPECTING

U.S. No. 2,192,404, J. J. Jakosky, Iss. 3/5/40, Appl. 10/30/47.

Methods and Apparatus for Electrical Exploration of the Subsurface—Movable electrode scheme. Tractor is used as a movable current electrode.

U.S. No. 2,200,096, E. E. Rosaire and S. S. West, Iss. 5/7/40, Appl. 10/22/37, Assign. Rosaire.

Geophysical Exploration by Time-Variant Electric Currents—Electric earth transients are repeated on a cathode-ray tube or the like and photographed to obtain an image having an improved signal-to-noise ratio.

U.S. No. 2,202,369, L. W. Blau, L. Statham, Iss. 5/28/40, Appl. 12/30/38, Assign. Standard Oil Development Co.

Electric Earth Transients in Geophysical Prospecting—Pickup electrodes are put on the same steady-state equipotential line. The transient observed is due to dissimilarity of steady and changing fields.

U.S. No. 2,204,436, D. S. Muzzey, Jr., Iss. 6/11/40, Appl. 2/5/38, Assign. Shell Development Company.

Commutation System—Electrical prospecting commutator with current-brush lifting cams and potential-brush shorting segments to improve low frequency operation.

GEOCHEMICAL PROSPECTING

U.S. No. 2,198,619, Leo Horvitz, Iss. 4/30/40, Appl. 6/24/37, Assign. E. E. Rosaire.

Geochemical Exploration—Gas evolved from soil samples is dehydrated and then burned. Products of combustion are analyzed to determine water content whereby the free and combined hydrogen content of the gas sample may be determined.

GRAVIMETRIC PROSPECTING

U.S. No. 2,203,293, Hart Brown, Iss. 6/4/40, Appl. 4/28/39.

Force Measuring Device—Calibrating weight for a gravimeter is lowered onto the mass by means of a special retaining and positioning device.

SEISMOGRAPH PROSPECTING

U.S. No. 2,189,741, J. P. Minton, Iss. 2/6/40, Appl. 11/17/37, Assign. Socony-Vacuum Oil Company.

Seismograph Blasting Cap—Blasting cap has two bridge wires: One in the detonator and one placed elsewhere so that it is not ruptured until the explosion occurs.

U.S. No. 2,192,972, A. I. Innes, Iss. 3/12/40, Appl. 10/21/37, Assign. Geophysical Research Corporation.

Seismic Surveying—Resistivity logs are made of various shot holes so that corresponding points may be correlated. Shots are fired in all holes at corresponding points after determining what point on the logs gives most favorable reflections.

U.S. No. 2,202,885, Theodor Zuschlag, Iss. 6/4/40, Appl. 10/21/37, Assign. Hans T. F. Lundberg.

Apparatus for Geophysical Exploration—Balancing circuit for measuring phase difference between two continuous-wave seismic pickups.

U.S. No. 2,203,272, N. R. Sparks, Iss. 6/4/40, Appl. 7/8/38. Assign. Stanolind Oil and Gas Company.

Apparatus for Determining Seismic Velocities—Vertical velocity is measured between seismometers at different depths in adjacent wells. Wave paths to the two seismometers are in line or at the same angle.

WELL LOGGING

U.S. No. 2,190,950, Gennady Potapenko, Iss. 2/20/40, Appl. 11/3/37.

Apparatus for Determining the Inclination and Direction of a Bore Hole—Pendulums move slide-weights on tuning fork prongs to vary frequency. These elastic vibrations are transmitted to the surface where frequencies are determined and the inclination of the well-bore determined. A two-component arrangement with pendulum axes at right angles, is used.

U.S. No. 2,190,141, C. P. Walker, Iss. 2/13/40, Appl. 4/29/39.

Pressure-Wave Velocity Measuring System—In connection with sonic fluid-level indicators for wells, a wave-resonant tube used to determine the velocity of sound in the gases of a well.

U.S. No. 2,196,314, R. E. Lee, Iss. 4/9/40, Appl. 2/14/38, Assign.—1/2 to J. E. Reynolds.

Method of Measuring Inherent Terrestrial Magnetism of the Earth's Crust—For the purpose of determining tectonics of the subsurface strata penetrated by a drill, a coil is vibrated axially in the drill head. Solenoids provide the necessary movement. The drill stem contains conductors with connectors at the joints.

U.S. No. 2,197,453, G. L. Hassler, Iss. 4/16/40, Appl. 1/3/38, Assign. Shell Development Company.

Method of Underground Exploration—Radioactivity well logger with amplifier in the well and a movable hood of known opacity for shielding the ionization chamber at will.

U.S. No. 2,197,493, L. G. Ellis, and J. W. Millington, Iss. 4/16/40, Appl. 4/11/39, Assign. Sperry Sun Well Surveying Co.

Electrical Prospecting Apparatus—Construction of a high frequency coil for well logging (using Bazzoni and Razek method, U.S. Pat. No. 2,167,630) contained in a non-metallic nose of a protective casing, and capable of withstanding deep well pressures.

U.S. No. 2,197,571, J. W. Millington and W. T. Evans, Iss. 4/16/40, Appl. 10/3/38, Assign. Sperry-Sun Well Surveying Co.

Bore Hole Exploring Apparatus—Cable motion commutates D.C. thereby advancing a synchronous recorder motor step by step to advance the record tape in proportion thereto.

U.S. No. 2,199,367, L. F. Athy and H. R. Prescott, Iss. 4/30/40, Appl. 8/10/38, Assign. Continental Oil Company.

Method of Logging Bore Holes—Dip of strata is logged by passing current between

spaced surface electrodes so that it flows parallel to the strata at the well. Potential differences are measured between horizontally spaced electrodes and vertically spaced electrodes in the well. North-south and east-west dip components are measured separately by proper choice of surface electrodes. The component dips are combined to obtain total dip.

U.S. No. 2,199,705, J. C. Karcher Iss. 5/7/40, Appl. 6/25/38.

Apparatus for Making Electrical Surveys of Bore Holes—The well bore is simultaneously logged for resistivity and polarization effects with a single cable by using a vibrating switch to connect ohm-meter and potentiometer alternately.

U.S. No. 2,200,476, W. D. Mounce Iss. 5/14/40, Appl. 12/31/35, Assign. Standard Oil Development Co.

Measurement of Acoustical Properties of Materials—Acoustic well logging. Velocity is measured by thyratron-tube circuit which allows a condenser to charge during the interval between transmission and reception of an acoustical signal between spaced transmitter and receptor in a well bore. Voltage built up on the condenser indicates the travel time. Acoustic impedance and attenuation may also be measured.

U.S. No. 2,203,176, W. J. Opocensky, Iss. 6/4/40, Appl. 4/1/39.

Time Controlled Subterranean Camera—Clockwork winds up a cord which trips a camera shutter. Tripping shutter closes contact and fires photo-flash lamps.

U.S. No. 2,203,720, C. R. Dale, Iss. 6/11/40, Appl. 12/10/34, Assign. Dale Service Corporation.

Apparatus for Detecting Water Intrusion in Bore Holes—Light transmission of well mud is used as an indication of water ingress. Uses photocell microammeter at the surface, and L-shaped fluid passage, opening at the bottom of the instrument casing.

U.S. No. 2,203,730, C. H. Johnson, Iss. 6/11/40 Appl. 1/27/39.

Method and Apparatus for Determining the Strike and Dip of Subsurface Strata—Magnetic polarization of known orientation is impressed on rock at bottom of bore hole. Measurement of the direction of polarization in the sample removed, then provides an azimuthal index whereby the original position of the sample in the earth can be determined.

U.S. No. 2 ,204,196, A. G. H. Straatman, Iss. 6/11/40, Appl. 11/7/38, Assign. Shell Development Company.

Method and Apparatus for Determining the Nature of Bore-Hole Fluids—An oscillator in the well is connected to immersed electrodes so that the effect of the well fluid on the oscillator frequency or the anode current in the tube circuit may be due either to the capacity or the self e.m.f. and resistance between the electrodes.

U.S. Reissue No. 21,383, C. P. Walker, Iss. 3/5/40 Appl. 12/4/39.

Method of Determining Fluid Density, Fluid Pressure and the Production Capacity of Oil Wells—Pertinent to acoustic fluid level determinations—The density of fluid column in the well is determined by change of fluid level caused by change of gas pressure. This may be done in an idle or pumping well. Density thus determined is of value in calculations for determining the productivity index of the well.

THE SOCIETY ROUND TABLE

CANCELLATION OF 1940 FALL MEETING

At a meeting of the Executive Committee held May 25, 1940, in Tulsa, Oklahoma, it was unanimously agreed that no semi-annual meeting would be held in the Fall It was decided at the same meeting that the 1941 Annual Meeting would be held in Houston, Texas, concurrently with that of the American Association of Petroleum Geologists.

ANNOUNCEMENT OF 1941 ANNUAL MEETING

The Executive Committee announces that the 1941 Annual Meeting of the Society of Exploration Geophysicists will be held April 1, 2, and 3, in Houston, Texas. The Rice Hotel has tentatively been selected as headquarters of the Society during the meeting.

Individuals wishing to prepare papers for presentation at the Annual Meeting are requested to contact Dr. H. B. Peacock, Vice-President of the Society, at 825 Esperson Building, Houston, Texas.

The Convention of the American Association of Petroleum Geologists will be held at the Rice Hotel, Houston, Texas, April 2, 3, and 4, it has been announced by Association officers.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

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O. T. Lawhorn, F. J. Williams, Barney Fisher

Lothrop Hedge Bailey
L. L. Nettleton, R. D. Wyckoff, E. A. Eckhardt

Charles Blizard Bazzoni
E. A. Eckhardt, B. B. Weatherby, L. W. Blau

Charles Louis Morehead Blocher
Josiah Taylor, G. W. Carr, Floyd Willis, Jr.

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O. C. Lester, Jr., Andrew Gilmour, L. Y. Faust

TRANSFER FROM ASSOCIATE TO ACTIVE STANDING

(Executive Order C-21)

Paul Frederick Browning
Alexis Martin Eichelberger, Jr.
Francis Archibald Roberts

PERSONAL ITEMS

(Members are requested to send material for publication herein to J. F. Gallie, P.O. Box 777, Austin, Texas.)

T. F. JOHNSTON, formerly with the Texas Company, is now in the Electrical Engineering Department of Iowa State College, Ames, Iowa.

GEORGE A. SULLIVANT, newly-elected associate member of the Society, is returning to the States shortly from Medan, Sumatra. He should therefore be addressed at 1311 Republic Bank Building, Dallas, Texas.

"Some Reflections on Seismic Prospecting," a paper prepared by E. A. ECKHARDT on improvements in explosives and blasting techniques brought about by close cooperation between powder companies and geophysical operators, appeared in the April issue of *The Explosives Engineer*. This journal is published by the Hercules Powder Company at Wilmington, Delaware. M. R. BUDD, an applicant for associate membership whose name is published in this issue of GEOPHYSICS, is Associate Editor of *The Explosives Engineer*.

ELLIOTT SWEET, President of the Sweet Geophysical Company, now has his offices in Los Angeles. His residence address is Apartment 206, 1924 N. Argyle Avenue, Hollywood, California.

W. W. NEWTON, formerly a Supervisor for Geotechnical Corporation, has been elected Vice-President of that organization, ROLAND F. BEERS has advised the Society. He now has offices at 1702 Tower Petroleum Building, Dallas, Texas, while his residence address is 4416 University Boulevard in that city.

CARL L. BRYAN, who was in Denmark during the German invasion of that country, has returned to the States with Mrs. Bryan and other American members of the prospecting party. Mr. Bryan is associated with the Gulf Research and Development Company, P.O. Drawer 2038, Pittsburgh, Pennsylvania.

F. H. AGEE, Party Chief with the National Geophysical Company of Dallas, Texas, is now located in Cuba. His address is Apartado 5, Los Palacios, Prov. Pinar del Rio, Cuba.

WALTER D. BAIRD of Geophysical Service, Inc., has been transferred from Hanford to Stockton, California, where he may be addressed at P.O. Box 1088.

On April 22, VINCENT EMANUEL advised the Society that his address was c/o Azienda Generale Italiana Petroli, Borgo Antini 3, Parma, Italia.

HUBERT N. HALL of the Continental Oil Company has been transferred to Tulare, California, where he may be addressed at P.O. Box 1211.

NATHAN C. DAVIES, consulting geologist, has moved from Fairfield to Centralia, Illinois. In his new location he will be associated with R. H. VAN GELDER. The postal address is P.O. Box 252, Centralia, Illinois.

J. C. HEGGBLOM of the Gulf Research and Development Company may be addressed c/o Western Gulf Oil Company, P.O. Box 903, Fresno, California.

H. H. SISSON has left Austin to return to Palacios, Texas.

J. P. FARIS, JR., has been transferred from Ft. Logan, Colorado, to Ft. Sam Houston, Texas.

B. M. BENCH has left the Geotechnical Corporation. He may be addressed c/o V. G. Bench, 6935 Crandon Avenue, Chicago, Illinois.

S. ZIMERMAN has been transferred from Meridian, Mississippi, to Gettysburg, South Dakota, where he may be addressed at P.O. Drawer 10. Mr. Zimerman is a Party Chief for the Carter Oil Company.

E. L. DEGOLYER returned to Dallas, Texas, upon completion of the second term at the University of Texas in Austin, where he had been serving as a distinguished professor. His Dallas address, as before, is c/o DeGolyer, MacNaughton and McGhee, Continental Building.

KARL DYK is Party Chief for the Stanolind Oil and Gas Company, P.O. Box 591, Tulsa, Oklahoma.

W. HARLAN TAYLOR of the Petty Geophysical Engineering Company has been appointed Supervisor of the Gulf Coast District, with headquarters in Houston, Texas.

E. T. NICHOLS has been transferred from Babo, Dutch New Guinea, to c/o N. P. P. M., Paleisweg 33, Medan, Sumatra, N. E. I.

V. G. GABRIEL has moved from Los Angeles to 290 S. Michigan Avenue, Pasadena, California.

C. EMERY BUFFUM has been transferred from Clarendon to Stratford, Texas. His postal address is P.O. Box 42.

FRANCIS H. CADY of the Carter Oil Company has been transferred from Okolona, Mississippi, to P.O. Box 1770, Meridian, Mississippi.

W. H. GAYMAN has advised the Society of his new address, 235 N. Grinnell Drive, Burbank, California.

CHARLES F. REED, JR., Station Manager for Dowell, Inc., has been transferred from Bakersfield to Long Beach, California, where his postal address is P.O. Box 229.

AUSTIN N. STANTON is now Vice-President of the Texas Geophysical Company, Inc., with offices at 1409 Dallas National Bank Building, Dallas, Texas.

J. G. KEARBY has opened an office at 1041 Liberty Bank Building, Dallas, Texas, and will do geophysical consulting work.

NORMAN A. HASKELL of the Western Geophysical Company has been transferred to Bakersfield, California, with an office at 16 Crites Building in that city.

RALPH R. Brewer, JR., Party Chief with Stanolind Oil and Gas Company, is now located in St. John, Kansas, where he may be addressed at P.O. Box 513.

IRL SANDIDGE, JR., has left the employ of the Lone Star Gas Company. He may be addressed at P.O. Box 1112, Ft. Worth, Texas.

JOHN H. HODGSON has left the University of Toronto to accept a position with the Schlumberger Well Surveying Corporation, Jergins Trust Building, Long Beach, California.

W. D. NEFF has left Geophysical Service, Inc., to accept a position as Party Chief with the General Geophysical Company, with offices at 2514 Gulf Building, Houston. Texas.

F. F. CAMPBELL, Party Chief for the Amerada Petroleum Corporation, has been transferred to Victoria, Texas. His postal address is P.O. Box 704.

V. E. CHILD, Party Chief with the Texas Company, may be addressed at P.O. Box 2332, Houston, Texas.

PAUL M. TUCKER of the Carter Oil Company may be addressed c/o H. T. Abercrombie, Barnard, Kansas.

EDWARD J. JASINSKI of the National Geophysical Company is now located at Apartado 5, Los Palacios, Pinar del Rio, Cuba.

PAUL F. CLEMENT of the Gulf Research & Development Co. has been transferred from Long Beach to Bakersfield, California, where he may be addressed at P.O. Box 1468.

The Society does not have the correct addresses of the following members. Members knowing their present addresses are respectfully requested to communicate with J. F. Gallie, Business Manager of the Society, P.O. Box 777, Austin, Texas.

W. N. BOOTH
J. L. COPELAND
N. C. HUNSAKER
J. G. KOENIGSBERGER
C. L. MACKEY
E. W. MARKWARDT
Z. A. MITERA
E. J. OWEN
R. B. WAGNER